NASA
SPACE VEHICLE
DESIGN CRITERIA
(CHEMICAL PROPULSION)

NASA SP-8041

CAPTIVE-FIRED TESTING OF SOLID ROCKET MOTORS

MARCH 1971

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, part of the series on Chemical Propulsion, is one such monograph. A list of all monographs issued prior to this one can be found on the last page of this document.

These monographs are to be regarded as guides to design and not as NASA requirements, except as may be specified in formal project specifications. It is expected, however, that these documents, revised as experience may indicate to be desirable, eventually will provide uniform design practices for NASA space vehicles.

This monograph, "Captive-Fired Testing of Solid Rocket Motors," was prepared under the direction of Howard W. Douglass, Chief, Design Criteria Office, Lewis Research Center; project management was by John H. Collins, Jr. The monograph was written by James W. Kordig, Jr. of Hercules, Inc., and was edited by Russell B. Keller, Jr. of Lewis. To assure technical accuracy of this document, scientists and engineers throughout the technical community participated in interviews, consultations, and critical review of the text. In particular, Rex A. Nilson of United Technology Center, United Aircraft Corporation, Warren D. Poling of Lockheed Propulsion Company, Lockheed Aircraft Corporation, and Clarence F. Sanders of Rocketdyne Division, North American Rockwell Corporation, individually and collectively reviewed the monograph in detail.

Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Lewis Research Center (Design Criteria Office), Cleveland, Ohio 44135.

March 1971

For sale by the National Technical Information Service, Springfield, Virginia 22151 – Price $3.00

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in design, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into two major sections that are preceded by a brief introduction and complemented by a set of references.

The State of the Art, section 2, reviews and discusses the total design problem, and identifies which design elements are involved in successful design. It describes succinctly the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Design Criteria* and Recommended Practices.

The *Design Criteria,* shown in italic in section 3, state clearly and briefly what rule, guide, limitation, or standard must be imposed on each essential design element to assure successful design. The *Design Criteria* can serve effectively as a checklist of rules for the project manager to use in guiding a design or in assessing its adequacy.

The Recommended Practices, also in section 3, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The Recommended Practices, in conjunction with the *Design Criteria,* provide positive guidance to the practicing designer on how to achieve successful design.

Both sections have been organized into decimally numbered subsections so that the subjects within similarly numbered subsections correspond from section to section. The format for the Contents displays this continuity of subject in such a way that a particular aspect of design can be followed through both sections as a discrete subject.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the designer.

Page intentionally left blank

CONTENTS

	Page
1. INTRODUCTION	1
2. STATE OF THE ART	3
3. DESIGN CRITERIA and Recommended Practices	57
REFERENCES	85
NASA Space Vehicle Design Criteria Monographs Issued to Date	91

SUBJECT	STATE OF THE ART		DESIGN CRITERIA	
DESIGN PROVISIONS FOR MOTOR TESTING	*2.1*	3	*3.1*	57
Measuring Thrust	*2.1.1*	3	*3.1.1*	57
Provisions for Dynamic Thrust Loads	*2.1.1.1*	3	*3.1.1.1*	57
Provisions for Motor-Attitude Loads	*2.1.1.2*	6	*3.1.1.2*	57
Provisions for Spin and Centrifuge Loads	*2.1.1.3*	6	*3.1.1.3*	58
Measuring Chamber and Igniter Pressure	*2.1.2*	6	*3.1.2*	58
Provisions for Dynamic Pressure Loads	*2.1.2.1*	7	*3.1.2.1*	58
Provisions for Static Pressure Loads	*2.1.2.2*	8	*3.1.2.2*	59
Provisions for Attachment Loads	*2.1.2.3*	8	*3.1.2.3*	59
Provisions for Thermal Loads	*2.1.2.4*	8	*3.1.2.4*	60
Preventing Nozzle Flow Separation	*2.1.3*	8	*3.1.3*	60
Provisions for Pressure Matching	*2.1.3.1*	11	*3.1.3.1*	60
Provisions for Pressure Variation	*2.1.3.2*	11	*3.1.3.2*	61
Spin and Centrifuge Testing	*2.1.4*	12	*3.1.4*	62
Provisions for Increased Chamber Pressure	*2.1.4.1*	12	*3.1.4.1*	62
Provisions for Increased Thrust	*2.1.4.2*	12	*3.1.4.2*	62
Provisions for Increased Char and Erosion	*2.1.4.3*	12	*3.1.4.3*	62

SUBJECT	STATE OF THE ART		DESIGN CRITERIA	
Counteracting Combustion Residue	*2.1.5*	13	*3.1.5*	63
Provisions for Increased Char and Erosion	*2.1.5.1*	14	*3.1.5.1*	63
Provisions for Throat Deposition	*2.1.5.2*	14	*3.1.5.2*	64
Counteracting External Heating and Cooling	*2.1.6*	14	*3.1.6*	64
Protection From Plume Radiant Heat	*2.1.6.1*	15	*3.1.6.1*	64
Protection From Plume Blowback	*2.1.6.2*	15	*3.1.6.2*	65
Protection From Convective Heating	*2.1.6.3*	16	*3.1.6.3*	66
Protection From Environmental Temperatures	*2.1.6.4*	17	*3.1.6.4*	66
Measuring Ballistically Related Phenomena	*2.1.7*	17	*3.1.7*	67
Provisions for Dynamic and Static Pressure Loads	*2.1.7.1*	18	*3.1.7.1*	67
Provisions for Attachment Loads	*2.1.7.2*	18	*3.1.7.2*	67
Provisions for Thermal Loads	*2.1.7.3*	18	*3.1.7.3*	67
Measuring Other Phenomena	*2.1.8*	18	*3.1.8*	68
EQUIPMENT AND PROCEDURES FOR MONITORING MOTOR PHENOMENA DURING TESTING	*2.2*	21	*3.2*	68
Thrust	*2.2.1*	21	*3.2.1*	68
Range and Capacity	*2.2.1.1*	22	*3.2.1.1*	68
Dynamic Response	*2.2.1.2*	22	*3.2.1.2*	68
Test Stand Alignment	*2.2.1.3*	24	*3.2.1.3*	70
Test Stand Calibration	*2.2.1.4*	24	*3.2.1.4*	70
Test Stand Transverse Vibration	*2.2.1.5*	24	*3.2.1.5*	70
Motor Growth	*2.2.1.6*	25	*3.2.1.6*	71
Motor Weight Change	*2.2.1.7*	25	*3.2.1.7*	71
Motor and Stand Balance	*2.2.1.8*	28	*3.2.1.8*	71
Protection From Environmental Temperatures	*2.2.1.9*	28	*3.2.1.9*	72
Test Stand Restraints	*2.2.1.10*	29	*3.2.1.10*	72
Pressure	*2.2.2*	29	*3.2.2*	72
Range and Capacity	*2.2.2.1*	32	*3.2.2.1*	72
Dynamic Response	*2.2.2.2*	34	*3.2.2.2*	73
Protection From External Heat	*2.2.2.3*	34	*3.2.2.3*	73
Protection From Internal Heat	*2.2.2.4*	35	*3.2.2.4*	74
Prevention of Plugging	*2.2.2.5*	35	*3.2.2.5*	74
Detection of Pressure Oscillations	*2.2.2.6*	36	*3.2.2.6*	75

SUBJECT	STATE OF THE ART		DESIGN CRITERIA	
Temperature and Heat Flux	*2.2.3*	36	*3.2.3*	76
Range and Capacity	*2.2.3.1*	39	*3.2.3.1*	76
Response Time	*2.2.3.2*	39	*3.2.3.2*	76
Location	*2.2.3.3*	40	*3.2.3.3*	76
Placement	*2.2.3.4*	40	*3.2.3.4*	77
Reduction of Thermal Disturbance	*2.2.3.5*	42	*3.2.3.5*	77
Protection From Char and Erosion	*2.2.3.6*	43	*3.2.3.6*	78
Protection From Radiant Heat	*2.2.3.7*	44	*3.2.3.7*	79
Strain, Deflection, and Elongation	*2.2.4*	45	*3.2.4*	79
Range and Capacity	*2.2.4.1*	45	*3.2.4.1*	79
Location	*2.2.4.2*	47	*3.2.4.2*	79
Alignment	*2.2.4.3*	47	*3.2.4.3*	80
Size	*2.2.4.4*	49	*3.2.4.4*	80
Attachment	*2.2.4.5*	49	*3.2.4.5*	80
Placement	*2.2.4.6*	51	*3.2.4.6*	81
Calibration	*2.2.4.7*	51	*3.2.4.7*	81
Protection From Thermal Environment	*2.2.4.8*	51	*3.2.4.8*	81
Temperature Compensation	*2.2.4.9*	52	*3.2.4.9*	82
Shock and Vibration	*2.2.5*	52	*3.2.5*	82
Range and Capacity	*2.2.5.1*	53	*3.2.5.1*	82
Frequency Response	*2.2.5.2*	53	*3.2.5.2*	82
Critical Locations	*2.2.5.3*	53	*3.2.5.3*	82
Directional Placement	*2.2.5.4*	54	*3.2.5.4*	83
Attachment	*2.2.5.5*	54	*3.2.5.5*	83
Calibration	*2.2.5.6*	55	*3.2.5.6*	84
Protection From Thermal Environment	*2.2.5.7*	56	*3.2.5.7*	84

LIST OF FIGURES

Figure	Title	Page
1	Motor attachments for transmitting thrust during test	4
2	A spin-test stand and a centrifuge-test stand	5
3	A common means of measuring chamber pressure	7
4	Two methods employed to support a cluster of pressure transducers	9
5	Physical model of flow separation and static pressure characteristics	10
6	Rocket altitude cell T-3 at Arnold Engineering Development Center, Tennessee	11
7	Increased thrust caused by spin-firing	13
8	Plume blowback at the end of simulated altitude test	15
9	Convective heating during simulated altitude test	16
10	Two kinds of support brackets	19
11	Two common pressure fitting/retention devices	20
12	Two kinds of lightweight thrust collectors	23
13	Side linkages and buttresses to prevent transverse motion of motor and test stand	26
14	Vertical six-component thrust stand	27
15	Aluminum foil wrap as thermal protection on test stand, flexures, and cabling	30
16	Antiflight or motion restraints	31
17	Flush diaphragm and cavity type pressure transducers	32
18	A cluster of pressure transducers for measuring a wide range of pressures	33
19	Acoustic oscillations that may occur in a rocket motor	37
20	Influence of instability on rocket motor pressure-time history	38
21	Thermocouples and calorimeters on solid rocket motors	41

Figure	Title	Page
22	Multiple thermoplug	43
23	Exploded view of surface thermocouple	44
24	Aluminum foil thermal protection on linear potentiometers	46
25	Common locations for linear potentiometers and strain gages on filament-wound chamber during testing	47
26	Strain gages on a motor chamber	48
27	Accelerometers located on forward closure and aft dome to detect acoustic oscillations	50
28	Test fixture for back-to-back frequency calibration of an accelerometer	55
29	A universal flexure with split-nut locking mechanism	69
30	Recommended pressure transducer locations for acoustic oscillations	75
31	Recommended practices for mounting thermocouples—plug type specimen	78

CAPTIVE-FIRED TESTING OF SOLID ROCKET MOTORS

1. INTRODUCTION

Many tests are used for the evaluation of a solid rocket motor. Excluding flight tests, the most significant test is the captive firing of the complete motor. This monograph is restricted to consideration of testing by captive firing.

The term "captive-fired testing," as used in this monograph, refers to static-fired, spin-fired, or centrifuge-fired testing of a complete solid propellant rocket motor to verify design and to measure performance. Such testing may require that design provisions be made for the specific purpose of ensuring successful and accurate tests—particularly if the structural or thermal loads expected in a test are more severe than those that will be encountered in flight. In all cases, the methods used to measure ballistic-related phenomena must conform to the motor requirements and the test conditions in order to gain a meaningful assessment.

The history of captive-fired testing has revealed that the inability to obtain accurate and complete test data centers around two problem areas. This monograph explores these two areas: Design Provisions for Motor Testing, and Equipment and Procedures for Monitoring Motor Phenomena During Testing.

Solid-propellant rocket motors have failed during testing when adequate design provisions for testing were not made. For example, motor failure during testing has been attributed to an external thermal environment more severe than would be expected during flight. Motor failures have resulted from severe thermal degradation of the internal insulation and case during spin-fired testing, and partial failures have been caused by combustion residue that increased the char and erosion of internal insulation during static-fired testing. In other instances, test data have been lost or inaccurate data have been acquired as a result of inadequate design provision for measuring thrust, pressure, temperature, strains, or shocks. For example, (1) erratic and questionable pressure data have resulted from plugging of the pressure paths; (2) uncertainty of the precise location of thermocouple junctions in regions having large thermal gradients has yielded questionable temperature data; and (3) poor bonding of a strain gage to a rocket chamber has resulted in inaccurate and erratic strain data.

Within the current testing technology, procedures and equipment for conducting successful captive-fired testing have been developed, but they have not been organized and applied in a self-consistent and integrated guide to testing. In many instances, the test equipment used is the result of tradeoff of conflicting factors. For example, a pressure-measuring train may be filled with oil in order to obtain thermal isolation of the sensor, even though the high-frequency response of the train is degraded; or the achievement of maximum accuracy in test data may be too costly, and a tradeoff of accuracy versus cost may result in data that are acceptable but not of the maximum possible accuracy.

The purpose of this monograph is to set forth clearly the basic requirements for successful captive-fired testing. This monograph identifies and isolates the individual problems involved in designing for testing and in monitoring testing, and then provides specific and detailed guidance for handling these problems. In areas where tradeoffs must be made, the alternative approaches and the risks or consequences of each are discussed. This monograph was prepared for use in testing solid-propellant rocket motors intended primarily for space vehicle use. Testing refinements and details restricted to tactical military solid rockets or to motors employed to evaluate propellants or materials are outside the scope of this work.

2. STATE OF THE ART

2.1 Design Provisions for Motor Testing

A successful captive-fired test requires that the test objectives be known and that adequate provisions for achieving these objectives be made during motor design and test stand design. The problems involved in this effort and their current solutions are discussed below.

2.1.1 Measuring Thrust

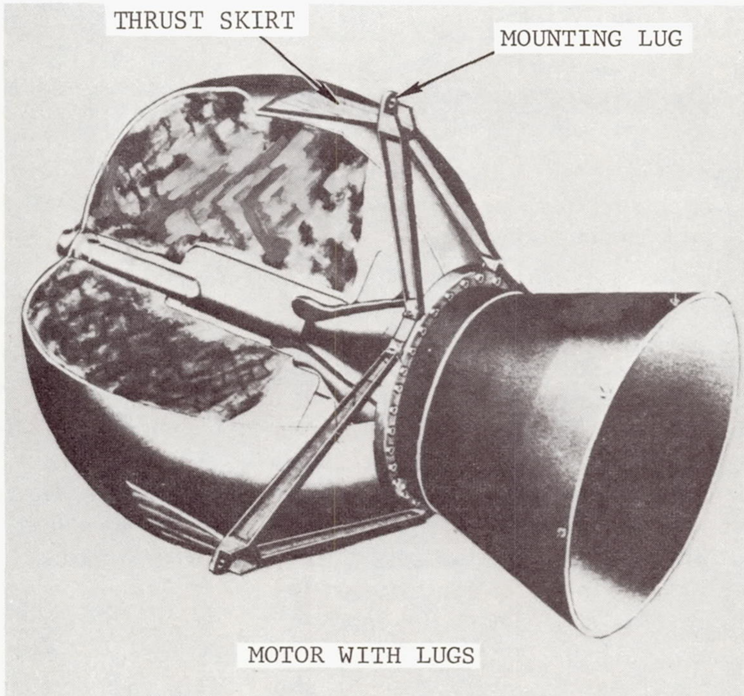
During testing, the thrust of a solid rocket motor is transmitted to a rigid buttress through a thrust collector. The thrust collector is attached to the motor by skirts, bosses, flanges, or lugs that are integral parts of the motor and are designed to support the motor and transmit thrust during flight. When thrust is measured during a test, the thrust load is transmitted to the buttress through a thrust load cell. Thrust collectors (or adapters) provide the interface between the skirts, bosses, flanges, or lugs and the load cell. Figure 1(a) shows both lugs and an aft skirt being used as attachments for transmitting thrust. Figure 1(b) shows a thrust collector (or adapter) interfacing with an aft skirt on a motor having no forward skirt. This arrangement is not a common test setup, but it illustrates the basic principles involved.

Usually, the flightweight motor skirt, boss, flange, or lug is strong enough to withstand the various loads that are imposed during static testing or during spin or centrifuge testing. (Spin or centrifuge testing is performed with the test stands shown in fig. 2.) Occasionally, however, the maximum thrust load, the maximum gravitational load as affected by motor attitude, or the spin or centrifuge load occurring during a test is more severe than provided for in the hardware designed for flight. In this event, the hardware must be modified to withstand the test condition.

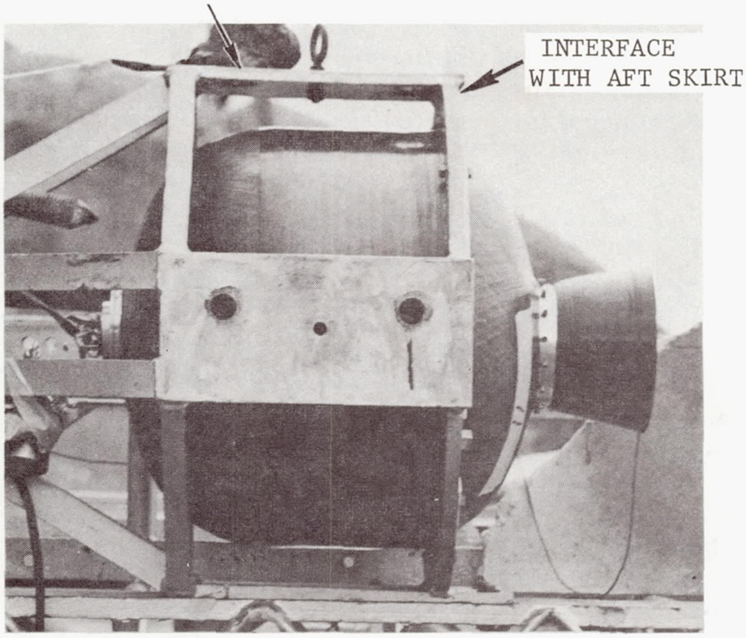
2.1.1.1 Provisions for Dynamic Thrust Loads

Dynamic thrust loads during testing at times exceed those that occur during flight because the dynamic response of the test stand and thrust adapters amplifies the imposed force, thereby increasing the loads on the thrust-transmitting skirts, bosses, flanges, or lugs (ref. 1). It is possible, in extreme cases, for dynamic loads to be twice as great as the applied thrust load from the motor. The dynamic load factor depends on the shape of the thrust transient. With slow-rising thrust curves, the load factor will normally be small; with fast-rising thrust curves and low-frequency motor/stand systems, the dynamic load factor can be large.

Both the thrust-transmitting hardware attached to a motor and the motor chamber itself have been subjected to critical stresses by heavy dynamic thrust loads that caused mechanical failure of the attachment. To prevent failure and to achieve good dynamic

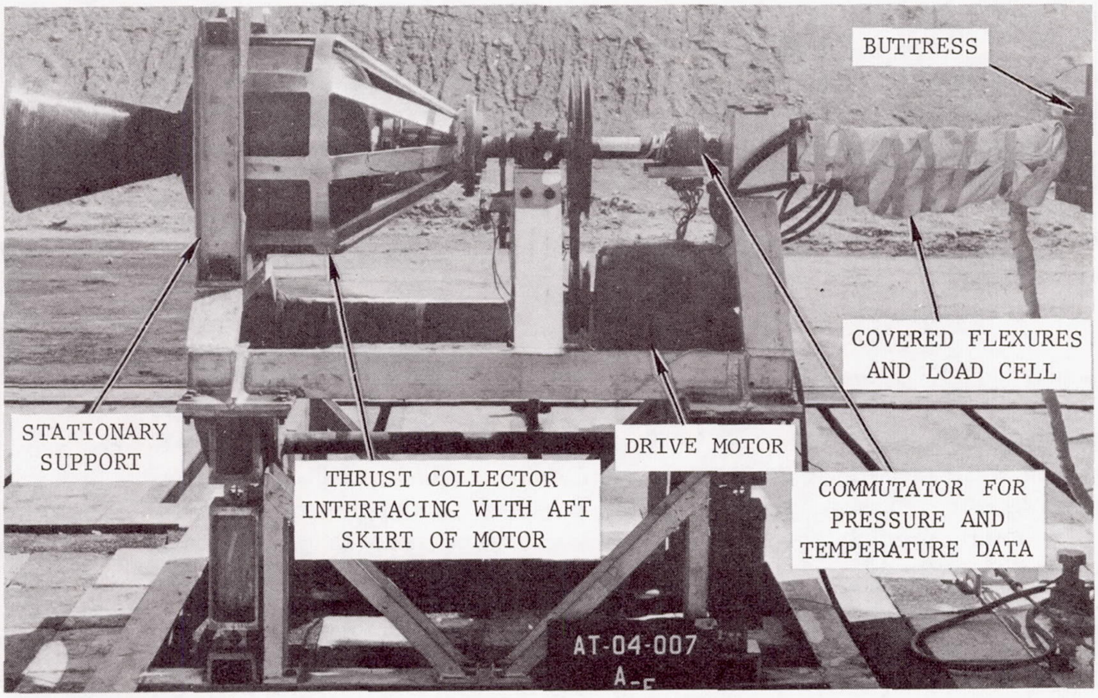


THRUST COLLECTOR

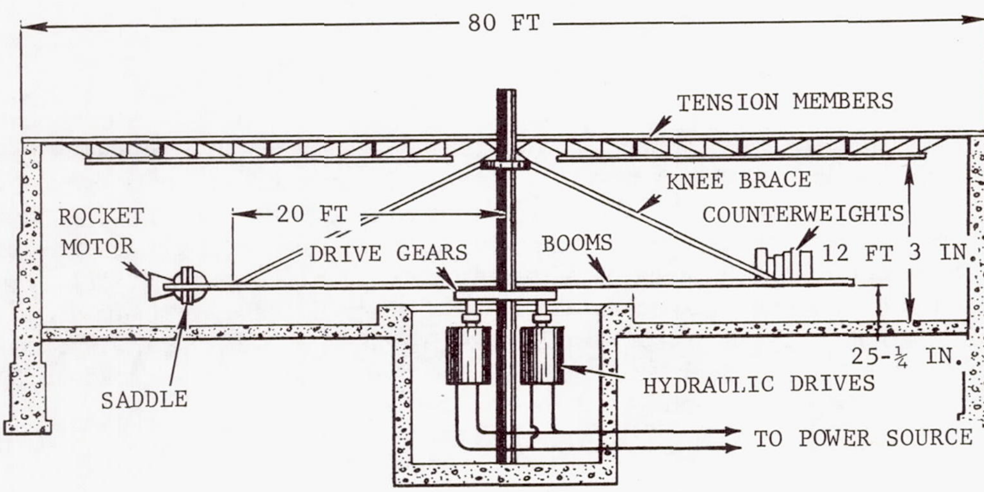


MOTOR WITH AFT SKIRT

Figure 1.—Motor attachments for transmitting thrust during test.



SPIN-TEST STAND



CENTRIFUGE-TEST STAND

Figure 2.—A spin-test stand and a centrifuge-test stand.

response, some items of thrust-transmitting hardware are strengthened to minimize deflections. Care is taken to ensure that the added mass of the strengthened hardware does not degrade the dynamic response of the thrust-transmitting system. Heavy dynamic thrust loads are sustained either by strengthening, bracing, or supporting the motor attachments or by providing additional support for the load during testing.

Occasionally, to reduce the load of a flightweight skirt, the method of transmitting thrust during test is changed from the method used for flight; e.g., motor dome supports have been used to assist in transmitting thrust (ref. 2).

2.1.1.2 Provisions for Motor-Attitude Loads

Motor attitudes during testing are often different from those in flight. A motor may be mounted for testing with the nozzle up, down, or horizontal. The forces transmitted to attachment hardware, the constraints imposed on the motor, and the deformations of the motor during testing often are different from those occurring during operational handling and flight. Long motors supported by forward and aft skirts, when tested horizontally, are subjected to shear forces, axial loads, and bending moments that may not be present during flight. Deformations of long motors fired in a horizontal position may affect the ballistic characteristics of some propellants because the strain imposed on the propellant by the deformation causes an increase in the burning rate (ref. 3).

Severe loads and moments caused by motor attitude in testing usually are sustained by stiffening rings mounted around the attachment skirts. Long motors in the horizontal position often are supported in the center region to reduce sag.

2.1.1.3 Provisions for Spin and Centrifuge Loads

Spin tests occasionally are conducted at rotational velocities greater than those anticipated for spin-stabilized flight so that motor sensitivity to spin rate may be evaluated. Consequently, motor-support and thrust-transmission hardware are subjected to centrifugal and centripetal loads greater than will be experienced in flight, and the hardware is strengthened or reinforced to withstand these special test loads. To evaluate motor sensitivity to acceleration loads, centrifuge testing of motors occasionally is conducted at rotational velocities that result in centrifugal and centripetal simulated acceleration loads greater than those anticipated for flight, and again the load-sustaining hardware is strengthened or reinforced for the test loads.

2.1.2 Measuring Chamber and Igniter Pressure

Most tests of solid rocket motors require a means for measuring chamber and igniter pressures. Usually, small-diameter piping or tubing connected to threaded outlets or bosses on the motor chamber is used to transmit pressure to a transducer. The locations in the motor chamber for monitoring pressure are dependent upon several factors (described more fully in sec. 2.2.2); i.e., the locations are selected so that (1) the pressure path is short and dynamic response is not jeopardized; (2) the pressure path enters the chamber where gas velocities are low, deposition is unlikely, and plugging is not a problem; and (3) entrances are in a pattern so that acoustic oscillations can be measured if they occur. For convenience in monitoring both igniter and chamber pressure, the pressure paths are led through a metal closure that serves also as an igniter mounting base. Figure 3 illustrates a common method for measuring pressure.

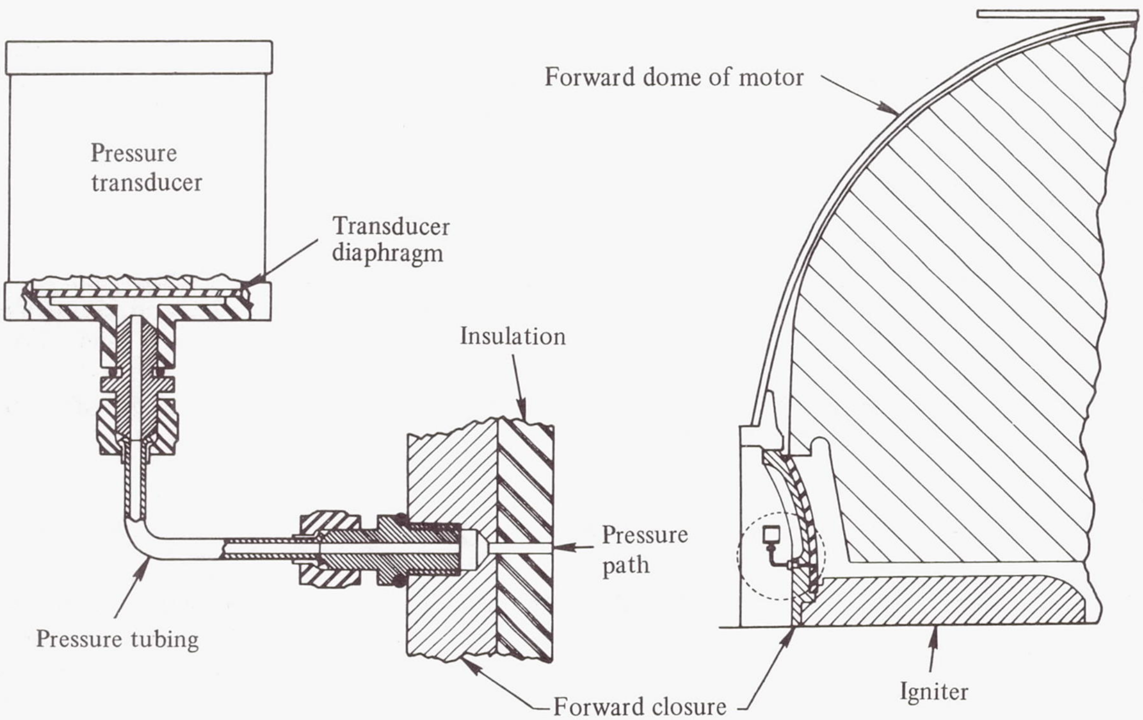


Figure 3.—A common means of measuring chamber pressure.

Separate and redundant pressure paths from both igniter and motor chamber are commonly used, and often more than one pressure transducer is attached to the piping or tubing at the terminus of each path. During testing, these pressure paths are subject to various failures from dynamic, static, and thermal loads. Suitable design provisions are made to avoid, prevent, or minimize such failures.

2.1.2.1 Provisions for Dynamic Pressure Loads

The rate of igniter pressure buildup often is quite high, and results in "ignition shock" (ref. 4). The impact or dynamic loading increases the stresses on the tubing and its connections, and on occasion has excited the pressure-measuring system into elastic vibration. Normally this problem is avoided by using support and holddown brackets that hold the tubing in place.

When the pressure path is led through elastomeric insulation, heavy loads from pressure buildup may deform the insulation material and close the path. Such closure is prevented by using a path of sufficient diameter.

2.1.2.2 Provisions for Static Pressure Loads

Pressure paths from the chamber and igniter may be subjected to short-duration pressures greater in magnitude than the subsequent chamber pressure. Proof and leak tests are commonly used to verify the adequacy of the pressure path design.

2.1.2.3 Provisions for Attachment Loads

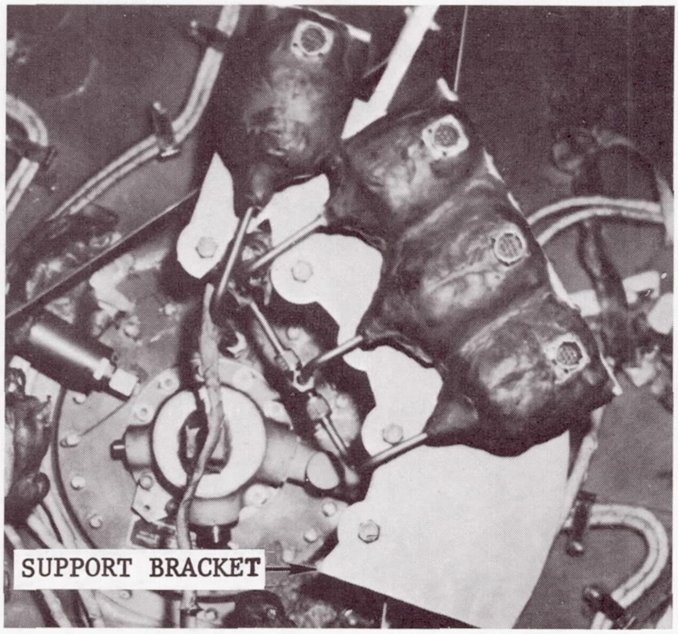
Pressure tubing and associated transducers and brackets attached to the motor may induce moments and loads on the chamber pressure-outlet region. Spin and centrifuge testing of motors produces added loads on the points where hardware is attached to the chamber. These attachment loads are usually distributed by support brackets (fig. 4(a)). Occasionally the entire region, including the transducer, is potted with zinc chromate putty to provide support and distribute the loads (fig. 4(b)).

2.1.2.4 Provisions for Thermal Loads

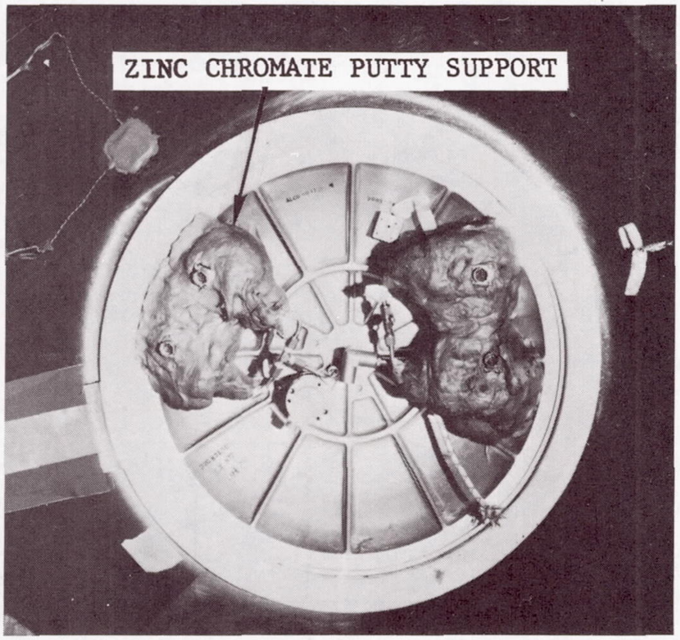
If the pressure paths are not filled with oil or grease, hot combustion gases enter and generate thermal loads. The stagnant hot gases usually cool rapidly by transfer of sensible heat to the surrounding pressure-path region. Various methods are employed to minimize thermal loads and keep temperatures in the pressure train to a minimum; the most common methods are (1) minimizing the volume of the pressure train and (2) cooling the transducer, tubing, and boss with water. However, if the design or installation of the pressure path is faulty, hot-chamber-gas leaks will impose thermal loads that cannot be accommodated, and the pressure-measuring system will fail, resulting in a motor failure.

2.1.3 Preventing Nozzle Flow Separation

Flow separation in the nozzle exit cone occurs when a nozzle designed for high altitude is tested at ground-level atmospheric pressure. Boundary-layer separation at the nozzle wall accompanied by oblique shock-wave formation occurs within the supersonic flow region of the nozzle (fig. 5) (ref. 5). These conditions affect the delivered impulse and make the subsequent calculation of vacuum impulse inaccurate. This shock-wave



(a)



(b)

Figure 4.—Two methods employed to support a cluster of pressure transducers.

formation within the nozzle exit cone may have an adverse effect on precise measurements of thrust alignment during a test.

Early work by Summerfield (ref. 6) defined criteria for separation in over-expanded nozzles. Separation occurs when $P_{exit} \leq 0.4\ P_{environment}$, where P_{exit} is the nozzle exit pressure and $P_{environment}$ is the test environment pressure. This relation is valid for conical divergents with half angles in the order of 15° and for chamber-to-environment pressure ratios greater than 16. If the divergence angle is increased above 15°, separa-

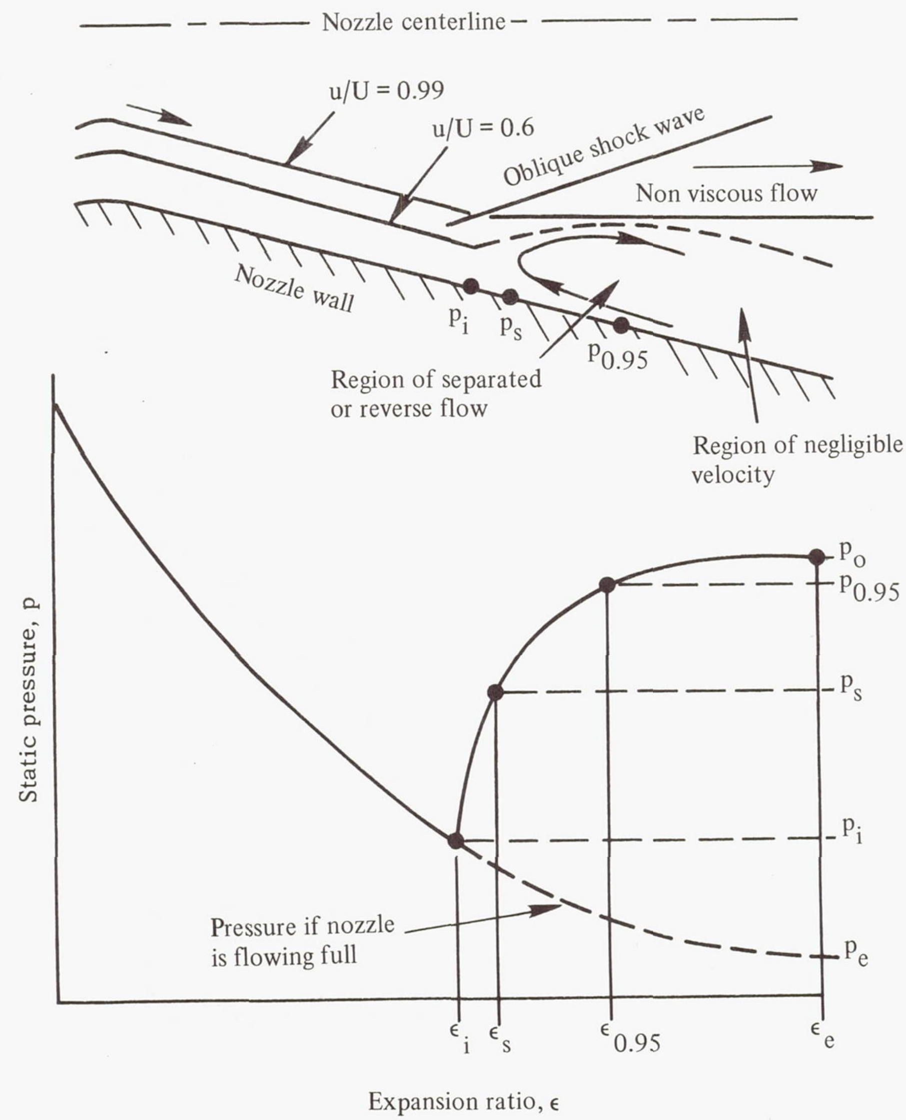


Figure 5.—Physical model of flow separation and static pressure characteristics (refs. 5 and 8).

tion is likely to occur when $P_{exit} > 0.4\ P_{environment}$. More recent data (ref. 7) on large rocket nozzles indicate that the ratio of P_{exit} to $P_{environment}$ may be as low as 0.286, instead of 0.4, when separation occurs. An analytical relationship between the separation pressure ratio, P_{exit} to $P_{environment}$, and the ratio of chamber pressure to environment for conical nozzles is given in reference 8. The separation pressure ratio is also influenced by nozzle divergence angle (ref. 9), exit contour, and nozzle length (ref. 10).

Ground-level atmospheric tests utilizing altitude nozzles often are conducted to evaluate objectives that are not related to accurate assessment of vacuum impulse. It is recognized that nozzle flow separation will occur in such tests. When accurate impulse performance verification is required, flow separation is held to a minimum.

2.1.3.1 Provisions for Pressure Matching

To prevent flow separation the nozzle exit pressure is matched to the environment test pressure by one of two methods: (1) the use of special test nozzles, or (2) the simulation of altitude pressure in a closed or open cell during captive-fired testing (fig. 6).

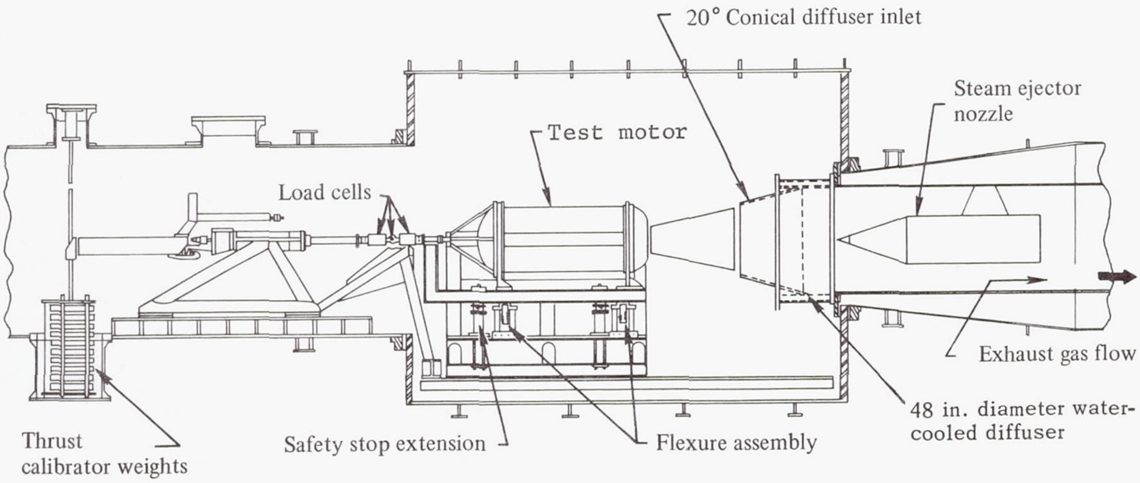


Figure 6.—Rocket altitude cell T-3 at Arnold Engineering Development Center, Tennessee.

2.1.3.2 Provisions for Pressure Variation

The nozzle exit pressure of some rocket motors will vary considerably during testing; this variation is usually a result of the desired progressive or regressive chamber pressures during motor action time. These conditions cause undesirable flow separation during a portion of the motor operation time. This separation is kept to a minimum by the selection of a test nozzle having the proper area ratio.

2.1.4 Spin and Centrifuge Testing

Spin or centrifuge testing of motors occasionally is necessary so that the load condition or dynamic environment of an actual mission can be simulated. The spin-test stand shown in figure 2 can rotate a 220-lb motor at about 300 rpm during captive-fired testing; the centrifuge-test stand in figure 2 can subject a motor as large as 6000-lb gross weight to about 43 g with the 20-ft boom revolving at 80 rpm during captive-fired testing.

Some solid rocket motors are influenced markedly by the dynamic environment generated by spin or centrifuge testing (refs. 11 and 12). Certain aluminized propellants in some grain configurations produce performance characteristics that deviate widely from those exhibited by the motor in static test or in flight. The main changes observed are increased pressure and thrust and increased char and erosion of insulation. Either effect may induce motor failure.

2.1.4.1 Provisions for Increased Chamber Pressure

Motor chamber pressures during spin testing are likely to be higher than those encountered at the same spin rate during flight because the longitudinal acceleration in flight tends to reduce spin sensitivity (the magnitude of chamber pressure increase with spin rate). As shown in references 12 and 13, many motors reach a threshold level above which increases in chamber pressure are proportional to increases in spin rate; below this threshold level, chamber pressure is almost uninfluenced by spin rate. Often, a spin-test development program involving gradually increasing spin rates to establish quantitative data on spin sensitivity has preceded final design. Any increase in chamber pressure over the design allowable generates stresses in the chamber and nozzle that may be critical. The chamber and nozzle are strengthened as necessary to maintain suitable margins of safety.

2.1.4.2 Provisions for Increased Thrust

The increased chamber pressure produced in spin tests is accompanied by a greater forward thrust level (fig. 7). The increased thrust produces increased loads on the thrust-transmission skirts, bosses, flanges, or mounting lugs attached to the chamber. This phenomenon has been observed in many tests; the methods for predicting it are reported in reference 14. When such increased thrust loads are predicted, the thrust-bearing test hardware is reinforced as described in section 2.1.1.1.

2.1.4.3 Provisions for Increased Char and Erosion

Propellant burn rates tend to be higher when the burn surface is normal to the acceleration vector and severe thermal degradation of motor internal insulation and chamber may occur from early depletion of propellant in thinly insulated regions.

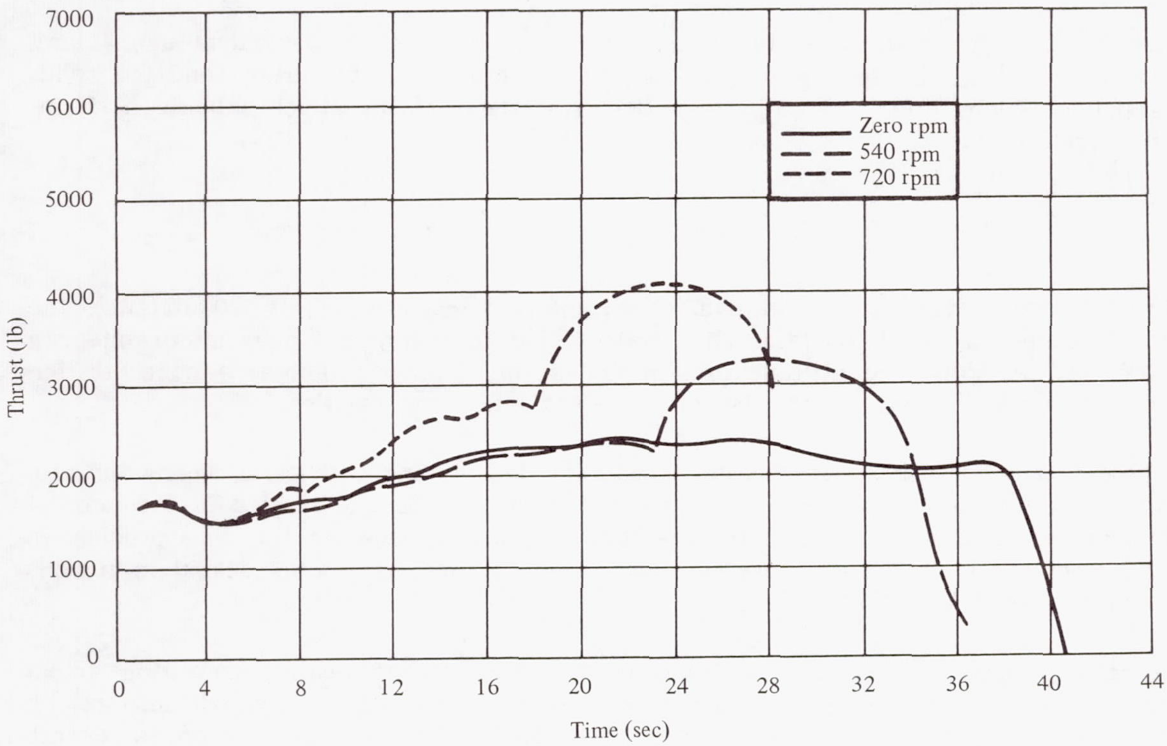


Figure 7.—Increased thrust caused by spin-firing (adapted from ref. 13).

For example, the increased propellant burn rate at the root of a star grain has resulted in premature exposure of the internal insulation during spin testing. An additional thickness of internal insulation is installed where necessary to provide adequate protection for the motor chamber.

2.1.5 Counteracting Combustion Residue

Combustion residue or slag from incomplete combustion of metallized propellants has been deposited in some solid rocket chambers during static testing, but it is believed that deposition during flight is unlikely because longitudinal forces prevent any accumulation of slag. This residue or slag has caused increased char and erosion of internal insulation during testing. In some instances, the chamber burned through (ref. 15); in others, the chamber overheated but did not fail (ref. 16).

Examination of ballistic data (thrust/pressure variation with time) reveals that deposition of combustion residue on nozzle surfaces occurs during testing but not during flight. Deposition takes place early in motor firing when free volume is small, propellant surfaces are close to the nozzle, and nozzle surfaces are cold. These conditions produce solidification of droplets of the exhaust products. When nozzle surfaces get hot, solidified residue melts and is washed downstream by nozzle flow forces. The thickness of the throat deposit is a time transient, dependent upon many factors including the temperature history of the nozzle throat surface and the solid-propellant composition (refs. 17 and 18). This deposit can affect ballistic performance (ref. 19).

2.1.5.1 Provisions for Increased Char and Erosion

Combustion residue collects in puddles on internal insulation (refs. 20 and 21), the result being increased insulator char and erosion that may endanger motor integrity (ref. 22). A horizontal attitude of a motor during testing promotes a concentration of combustion residue in the bottom of slots and liner cavities.

There is available little information concerning known and successful means for predicting when and where residue or slag will increase char and erosion of the internal insulation. Most often, cut-and-try methods are employed when the slag problem is encountered; i.e., additional insulation is added to the next motor design in regions of high char and erosion.

Generally, erosion of a nozzle throat is the same during testing as during actual flight. On the other hand, the rate and pattern of deposition on nozzle surfaces in tests are different from those in flight because longitudinal acceleration forces are absent during static test.

2.1.5.2 Provisions for Throat Deposition

Deposition predictions have been closely correlated with nozzle thermocouple response and internal ballistic performance (ref. 23). During the time when slag or residue is deposited on nozzle throat surfaces, interior ballistics are influenced, and chamber pressure is increased above normal because the throat area is reduced. When it is known that combustion residue will deposit on a nozzle throat surface, the usual practices are to assume a smaller throat area when predicting interior ballistics and, when necessary, provide additional structural strength so that the motor will withstand higher pressure.

2.1.6 Counteracting External Heating and Cooling

During testing, external surfaces of a rocket motor, including all external attachments and the test stand, are exposed to various thermal environments. Some motor failures during testing have been attributed to an external thermal environment hotter than provided for in the flight design (ref. 24). The nozzle exhaust plume is the primary source of external heating. When the nozzle is shortened so that the exit pressure matches more closely the ground-test pressure, the intensity of radiant heating to the motor usually is increased because of the shorter distance from the plume to the motor. Often secondary sources of external heating (e.g., solar heating and warm environments just before, during, and after testing) are important.

Undesirable motor heating is usually the problem, but exposure to cold weather may cool a motor below a prescribed temperature limit. When the cooled motor is ignited, the cold propellant grain or the cold insulator (or both) may crack because of reduced allowable strain; ballistic variations also may develop because of decreased burn rate of propellant and longer ignition transient.

2.1.6.1 Protection From Plume Radiant Heat

In some static-fired tests, motors have failed because external aft-end heating was more severe than had been predicted for flight. This heating is attributable to radiant heat from the nozzle exhaust plume (refs. 25 and 26). Current practices for protecting a test motor from this type of heating include use of reflective finishes on exposed surfaces, heat shields, heavier applications of external insulation, and water sprays.

2.1.6.2 Protection From Plume Blowback

In tests of solid rocket motors under simulated altitude conditions involving a diffuser, nozzle exhaust plume blowback over the motor and attachments has occurred during motor tailoff at diffuser breakdown (fig. 8). Plume blowback has resulted in extensive damage, caused anomalies in thrust data, and prevented acquisition of

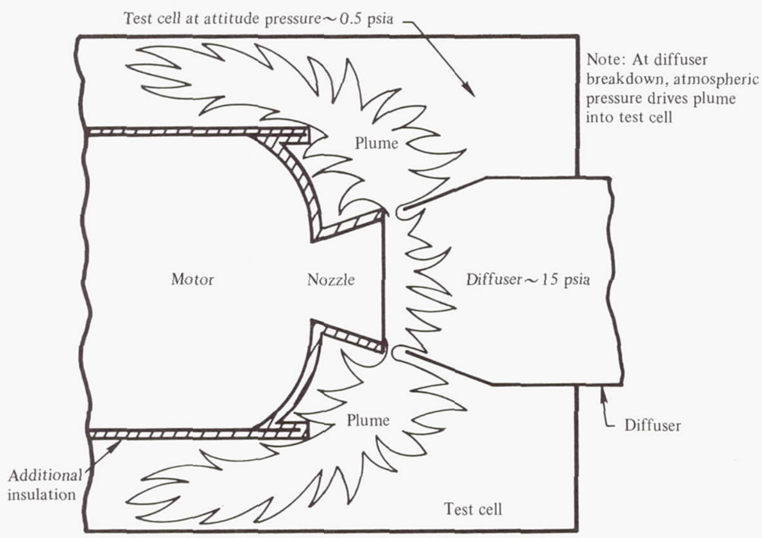


Figure 8.—Plume blowback at the end of simulated altitude test.

complete test results (ref. 27). Blowback is reduced by water spray or nitrogen purge; thermal protection (sec. 2.1.6.1) is employed to prevent damage.

2.1.6.3 Protection From Convective Heating

When any solid rocket motor is fired, hot nozzle exhaust gases circulate around the motor aft region. In the testing of multinozzle motors and motors confined in vacuum chambers for simulated altitude testing, this convective heating of the aft region is severe (ref. 28) and can lead to problems like those resulting from plume blowback (fig. 9). To prevent such overheating, the motor and its attachments are protected by appropriate means (sec. 2.1.6.1).

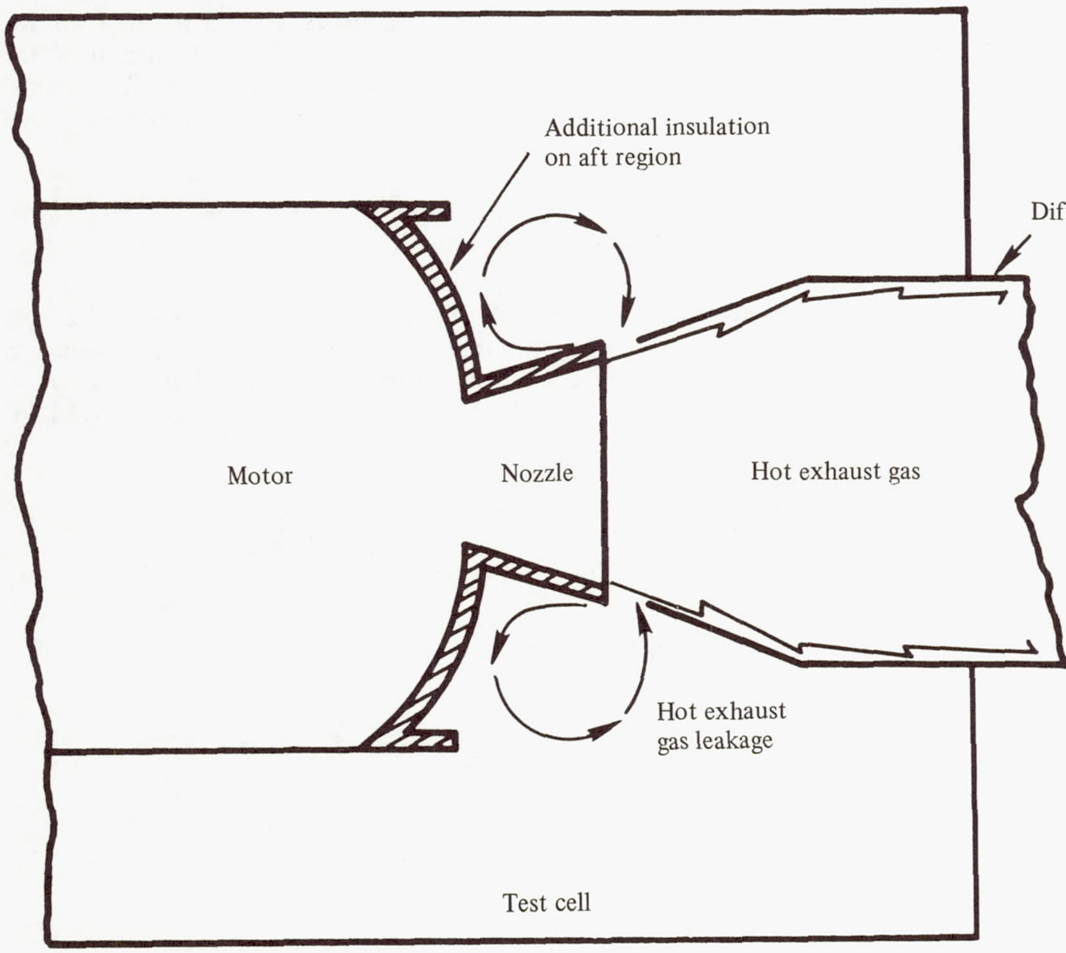


Figure 9.—Convective heating during simulated altitude test.

2.1.6.4 Protection From Environmental Temperatures

When environmental temperatures are significantly below or above the motor conditioning temperature, the motor may be excessively cooled or heated before and during the test. Current methods to maintain the motor and its attachments at a constant temperature include the use of temperature-controlled test bays, sunshades, removable blankets, and various covers. Frequently, nozzle-throat plugs or nozzle exit plane covers are used to help prevent external heating or cooling from affecting the motor interior before testing. In addition, every effort is made to keep exposure to the adverse environment at a minimum.

2.1.7 Measuring Ballistically Related Phenomena

Ballistically related phenomena may include temperature and heat flux; strain, deflection, and elongation; and shock and vibration. Most solid rocket motors are modified for testing by the addition of outlets or bosses and attachment brackets so that these phenomena may be measured. The motor modifications required for a particular test depend upon the objectives of the test and the measuring methods employed. Improper motor modification has resulted, in some instances, in total motor failure during testing and, in other instances, in failure to meet some test objectives (ref. 29). Usually there is close coordination among motor designers, test engineers, and instrumentation specialists to accomplish a satisfactory installation and avoid the possibility of failure.

Structure and insulation temperatures usually are measured by embedded thermocouples, and convective and radiant heat fluxes are recorded by calorimeters. Occasionally, provisions are made either to measure the location of propellant burn surfaces by means of thermocouples, electrical breakwires (refs. 30 and 31), or light-transmitting plastic rods (ref. 32) or to record propellant burn surface locations with X-ray film or the reflections of microwave radiation (ref. 33). Less frequently, provisions are made to measure the strain of structural components by means of embedded strain gages.

The locations for measuring ballistic phenomena are dependent primarily on the factors described in sections 2.2.3, 2.2.4, and 2.2.5, and to some extent on the transducer or measuring system employed. For example,

(1) Temperatures commonly are measured at locations on the aft dome of the motor case and near the nozzle throat; less frequently, they are measured at locations on the nozzle attach ring.
(2) Strain, deflection, and elongation are measured in regions considered critical for the specific design; usual locations are the motor case domes, the motor case dome/cylinder junctions, and the center of the motor case.

(3) Shock and vibration usually are measured at locations necessary for prediction of flight environments and at locations where the data are important for a variety of conditions involving test-stand and motor dynamics, key-event detection, and structural integrity verification.

For each example given, the location influences the selection of a transducer and vice versa, e.g., a location having large strain gradients requires strain gages that are small in size, and the selection of a thermocouple to measure temperature prevents measurements at in-wall locations where structural margins are low enough to prohibit drilling of holes.

2.1.7.1 Provisions for Dynamic and Static Pressure Loads

High-rate pressure buildup in the motor chamber at motor ignition and the steady high chamber pressures that follow produce ignition shock loads and steady pressure loads on the chamber and nozzle outlets or bosses and on the transducers and leads that are placed on a rocket motor to measure ballistically related phenomena. These loads are sustained by support brackets and by pressure fittings designed to withstand maximum pressure loads. Figure 10(a) depicts a support bracket of this type. (The failed bracket shown in fig. 10(b) is discussed in sec. 2.1.8.) Two common pressure fittings for leads are displayed in figure 11.

2.1.7.2 Provisions for Attachment Loads

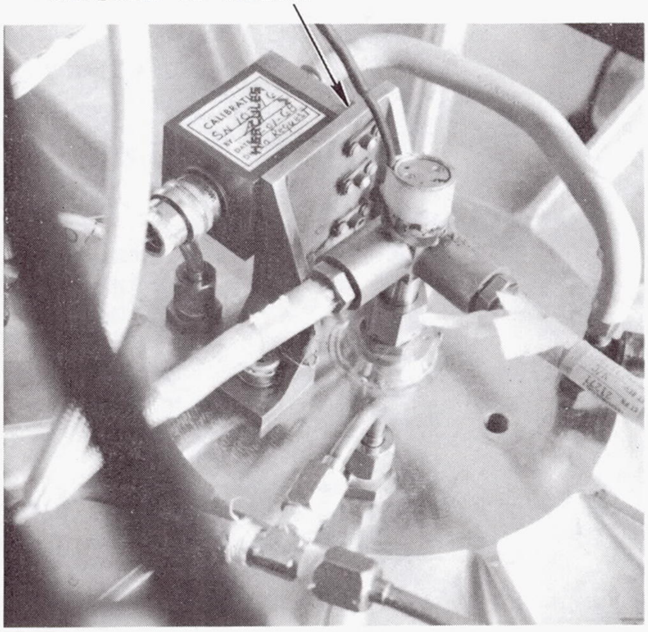
Transducers, support brackets, and cabling attached to a motor chamber may induce moments and loads at their attach points. Therefore, load-distributing pads are employed to avoid load concentrations.

2.1.7.3 Provisions for Thermal Loads

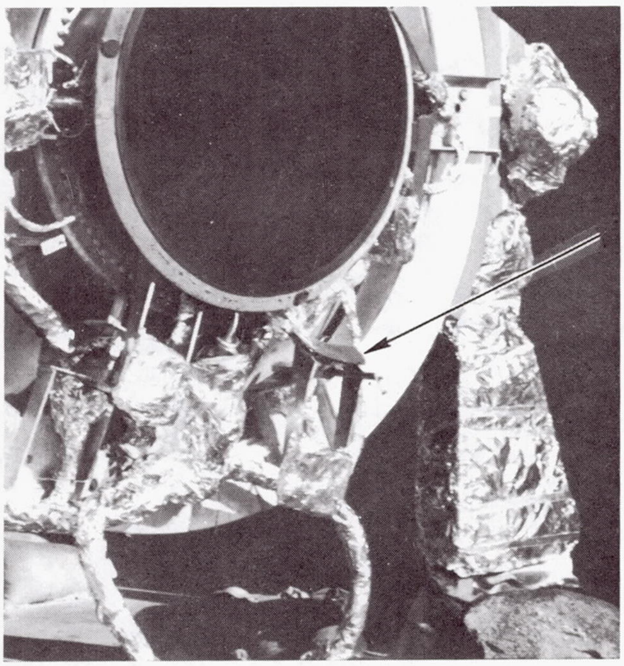
The exposure of transducers or sensor components and their lead wires to high temperatures and pressures during testing can jeopardize motor integrity. For example, a thermocouple was ejected after the region in which it was mounted was exposed to high temperatures; this resulted in motor and test failure (ref. 33). Positive retention devices are employed to prevent such failures and to ensure structural integrity. Figure 11(a) illustrates a simple but effective means of retaining lead wires in a filament-wound chamber, and fig. 11(b) shows a transducer gland with insulators and a heat-resistant sealant for use with a metal chamber.

2.1.8 Measuring Other Phenomena

Some solid rocket motors are modified for testing by providing transducers and cabling with required brackets and attachments so that certain data that may be of

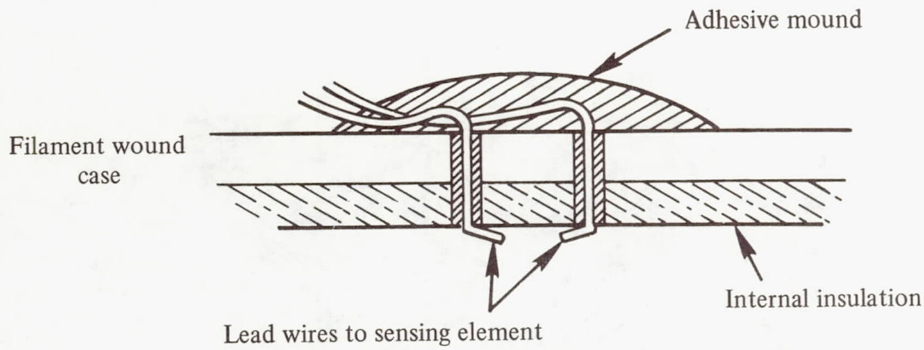


(a)

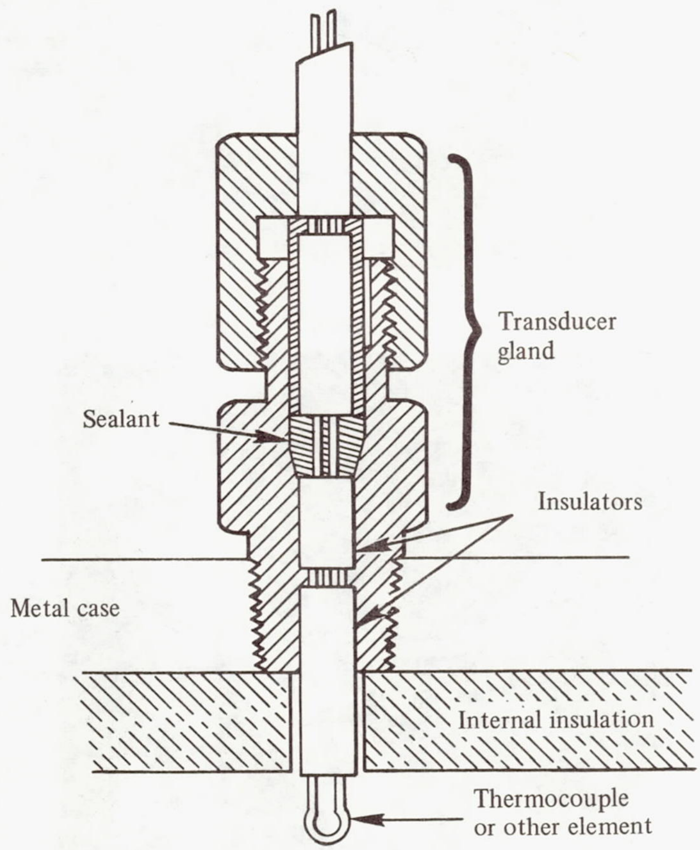


(b)

Figure 10.—Two kinds of support brackets.



(a)



(b)

Figure 11.—Two common pressure fitting/retention devices.

interest for a particular motor can be measured. For example, the measurement of nozzle movement or position during vectoring commonly is accomplished by attaching brackets to a nozzle and providing a spring-loaded motion sensor that bears upon the moving bracket. The attached bracket is constructed and installed so that it will sustain the dynamic, static, and thermal loads imposed during nozzle vectoring. Improper provisions for such installation have resulted in loss of data. Figure 10(b) shows a failed bracket that resulted in loss of nozzle movement data. The failure occurred in the adhesive bond joint of the bracket-to-nozzle attachment.

2.2 Equipment and Procedures for Monitoring Motor Phenomena During Testing

The means and methods by which ballistic and ballistically related phenomena are measured must preclude the possibility of the acquisition of inaccurate data or the loss of data. Additionally, personnel at all test sites recognize that accuracy requirements for test data are controlled generally by economics; frequently a tradeoff of accuracy versus cost yields data that are acceptable even though below the level of maximum possible accuracy. The critical factors involved in obtaining accurate and complete data are described below.

2.2.1 Thrust

Nearly all rocket motor tests conducted to assess performance require accurate measurement of the forward thrust. Occasionally, however, and for a variety of reasons, accurate measurements are not obtained or thrust data are questionable. Some of the problems and difficulties involved in thrust measurements are as follows:

(1) Thrust loads were appreciably larger than anticipated (usually during a motor development program), and load cells sustained loads above their rated capacities, thereby yielding inaccurate data.
(2) Rapid thrust changes during motor startup or ignition caused apparent thrust oscillations or "ringing" to be measured by the load cell because there was poor dynamic response to the actual thrust transient.
(3) Misalignment of motor and test stand components degraded the load-carrying capacity of transverse linkages and altered the spring constant of the forward thrust train; these conditions produced complex stand interactions resulting in erroneous thrust data.
(4) Lack of thrust stand calibration prevented correction of load cell readings so that an accurate value of the actual thrust delivered by the motor could be obtained.
(5) Motor weight changes or motor growth during a test influenced the accuracy of thrust measurements.
(6) High ambient temperatures during testing affected the accuracy of the thrust-measuring instruments.

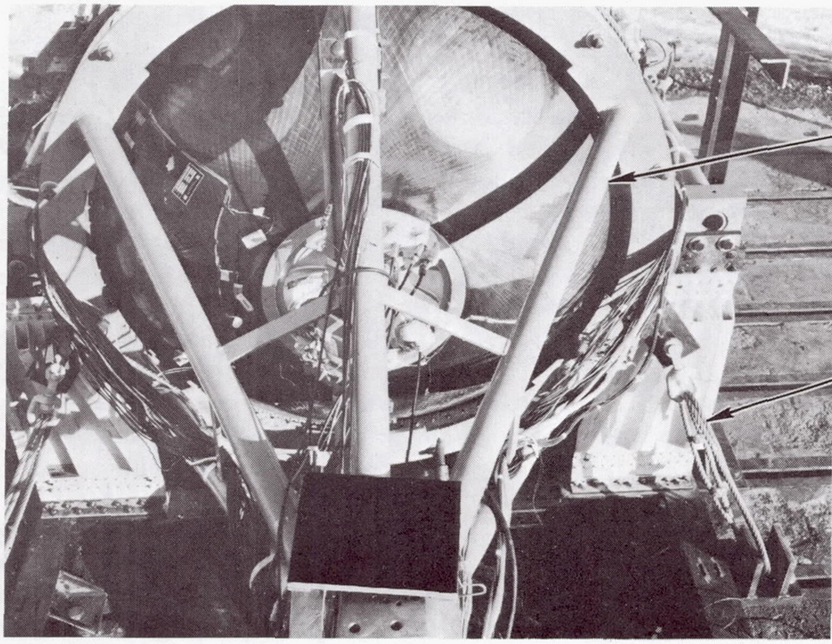
(7) Unnecessary vibration in spin, centrifuge, and static testing affected the accuracy of thrust measurements and in some cases damaged the motor.
(8) Transverse vibration of test stand and motor shook a test stand from its base.
(9) Motors and test stands have malfunctioned, and "static" tests without adequate antiflight restraints have jeopardized surrounding facilities and personnel.

2.2.1.1 Range and Capacity

Dual-bridge, bonded-strain-gage load cells are employed to monitor thrust. Load cells are usually employed up to about 125 percent of their rated capacity and remain mechanically safe up to about 200 percent. Dual-range load cells are employed to monitor widely different thrust levels; two cells with different ranges mounted in series and containing stops to prevent damage to the low-range cell have also been employed. Most installations incorporate universal flexures that are sized for expected thrust and deadweight loads. When data of lower accuracy are acceptable, flexures are not employed (ref. 34). Sizing of load cells and flexures influences system deflection, which in turn affects dynamic response to motor thrust transients.

2.2.1.2 Dynamic Response

The load cell is selected so that it will possess dynamic response adequate for the predicted motor thrust transients or variations (refs. 35, 36, and 37). Normally, neither a low rise rate nor a low decay rate of thrust requires high system dynamic response. When a high dynamic response is necessary (e.g., with high-acceleration motors and motors having very rapid ignition), the response is limited by motor and stand mass and stiffness of the thrust train, which includes the motor itself. Motor mass usually cannot be modified to improve dynamic response for test purposes. Thrust stand and collector or adapter mass are generally minimized by designing structural members that offer the greatest moment of inertia for a minimum area; two lightweight thrust collectors are shown in figure 12. Tubing (fig. 12(a)) will fail more readily from heat, and, therefore, a thrust collector constructed of tubing is less desirable than a solid-bar collector (fig. 12(b)). Construction materials vary; steel, because of its higher modulus, is preferred over aluminum for good dynamic response, but aluminum is often used when a nonsparking material is required or desired in the proximity of the solid propellant. To improve dynamic response, stiffness of the thrust train is usually kept high by keeping strains to a minimum in flexures, connectors, collector or load cells, and the rigid buttress. Also, strains are minimized by means of low-deflection-type load cells and universal flexures. Added damping may also be employed to provide better response to thrust transients. Adequate response to a thrust transient is achieved when the natural frequency of the system has a time period less than one-fourth the time period of the motor thrust transient.



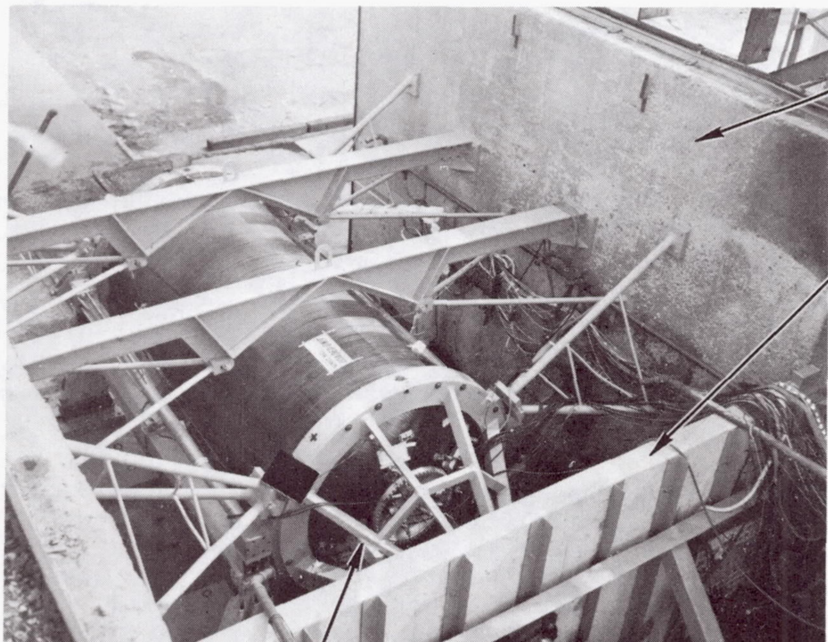


Figure 12.—Two kinds of lightweight thrust collectors.

2.2.1.3 Test Stand Alignment

Motor thrust can be measured accurately only when the motor and thrust stand, including all supports, are precisely aligned. Measured thrust is equal to actual thrust times the cosine of the angle of misalignment. Slight misalignment of only the forward thrust vector has produced small errors. For example, if the forward thrust vector is misaligned by the fairly large angle of 2° 34′ the inaccuracy in thrust measurement will be about one-tenth of 1 percent; for a relatively large misalignment of 4°, the inaccuracy in thrust measurement will be about one-fourth of 1 percent. Larger errors in thrust measurements have occurred when misalignment of stand supports or transverse linkages induced complex stand interactions that applied extraneous forces to the load cell. Occasionally, misalignment of transverse linkages is intentionally incorporated so that the regular motor growth or stand deflection during a test will move the linkages into alignment, the result being normal or orthogonal supports that permit improved accuracy of thrust measurement. The load-carrying ability of universal flexures decreases rapidly with small increases in angular misalignment. Consequently, a thrust stand with universal flexures usually is aligned so that linkage misalignment is no more than one-eighth of 1°. Alignment accuracy requirements vary considerably; consequently, alignment methods range from approximate line-of-sight techniques to the use of an alignment scope and telescopic transit when highest accuracy is required. When repetitive tests are conducted, precise alignment after the first test for each firing often is considered unnecessary when a dowel-in-place method of reestablishing alignment has been utilized.

2.2.1.4 Test Stand Calibration

Part of the thrust of a motor being tested deflects the thrust stand; thus the amount of thrust required for this deflection must be known. Depending upon the type of stand, the force required for thrust-stand deflection may be either positive or negative in sign and results from flexure restraint, interactions, and the inverted pendulum effect. Thrust-stand calibration generally is accomplished with load cells that have been calibrated with secondary standards that, in turn, usually have been calibrated by the National Bureau of Standards or some equivalent authority. In-place calibration by deadweight or by stand deflection versus applied force measurements are the most common methods currently in use. Often, physical stand calibration is conducted only on a new stand; economic considerations and accuracy requirements may preclude costly deadweight calibration for every repetitive test. Details of end-to-end calibration, which includes signal transmission and recording, are beyond the scope of this monograph.

2.2.1.5 Test Stand Transverse Vibration

Transverse mechanical vibrations of the motor and test stand are undesirable because, in extreme situations, they may cause the motor and stand to be shaken from their foundation. Applied transient side loads that may result from nozzle motion for thrust vectoring or from other sources during testing impose problems because they may induce, sustain, or amplify transverse vibrations. So that problems of this kind may be kept to a minimum, tests often are conducted to establish the transverse natural frequency of a test stand and motor. The problems associated with transverse vibration usually are aggravated in the testing of heavy motors because their greater weight results in low natural frequencies of vibration that may be close to the frequencies of an applied side load. These problems are overcome by using sufficiently large linkages and buttresses for side loads and by avoiding side loads that are applied at the transverse natural frequency of the test stand and motor. Figure 13 shows the linkages and buttresses for one side of a motor and part of a similar arrangement on the other side.

2.2.1.6 Motor Growth

Unrestrained motor growth in the longitudinal direction as a result of motor pressurization generally is allowed for in the design of the test stand. If provisions for longitudinal growth are not made, serious thrust stand misalignment will occur and errors in the measurement of thrust will result. The growth magnitudes usually depend upon absolute motor size, materials, and chamber pressure level. For large glass-filament-wound motor cases (15 ft long, 6 ft diameter), the growth in the longitudinal direction is as large as 1 in.; for large metallic motor cases (60 ft long, 10 ft diameter), the growth is about three-quarters of an inch. Smaller motors operating at relatively low pressures commonly experience considerably less longitudinal growth. Longitudinal growth is accommodated in a variety of ways. In one method, transverse flexures are offset a predetermined amount before testing so that motor growth during testing results in orthogonal support. More commonly, linear bearings, sleeves, wheels, or V-blocks are employed to provide little longitudinal restraint and considerable transverse restraint.

2.2.1.7 Motor Weight Change

During a captive-fired test, a motor loses weight steadily as propellant and combustible insulation are consumed. The effect of the weight loss on the accuracy of thrust measurements depends on the relative magnitudes of weight lost and thrust being measured. When the ratio of weight change to thrust is large (e.g., with long-burning motors as opposed to short-burning motors), the influence of weight change on the accuracy of thrust measurement is great. Usually, the influence is greatest with motors that are mounted vertically (figs. 13 and 14). The weight change generally is accounted for by adding it analytically to forward thrust data in computerized data reduction programs. For motors that are mounted horizontally for test purposes, weight change influences forward thrust by means of the inverse pendulum effect; this effect is created when the thrust train moves forward a small distance under the thrust load, and a component of the decreasing stand/motor mass is added to the load cell.

Figure 13.—Side linkages and buttresses to prevent transverse motion of motor and test stand.

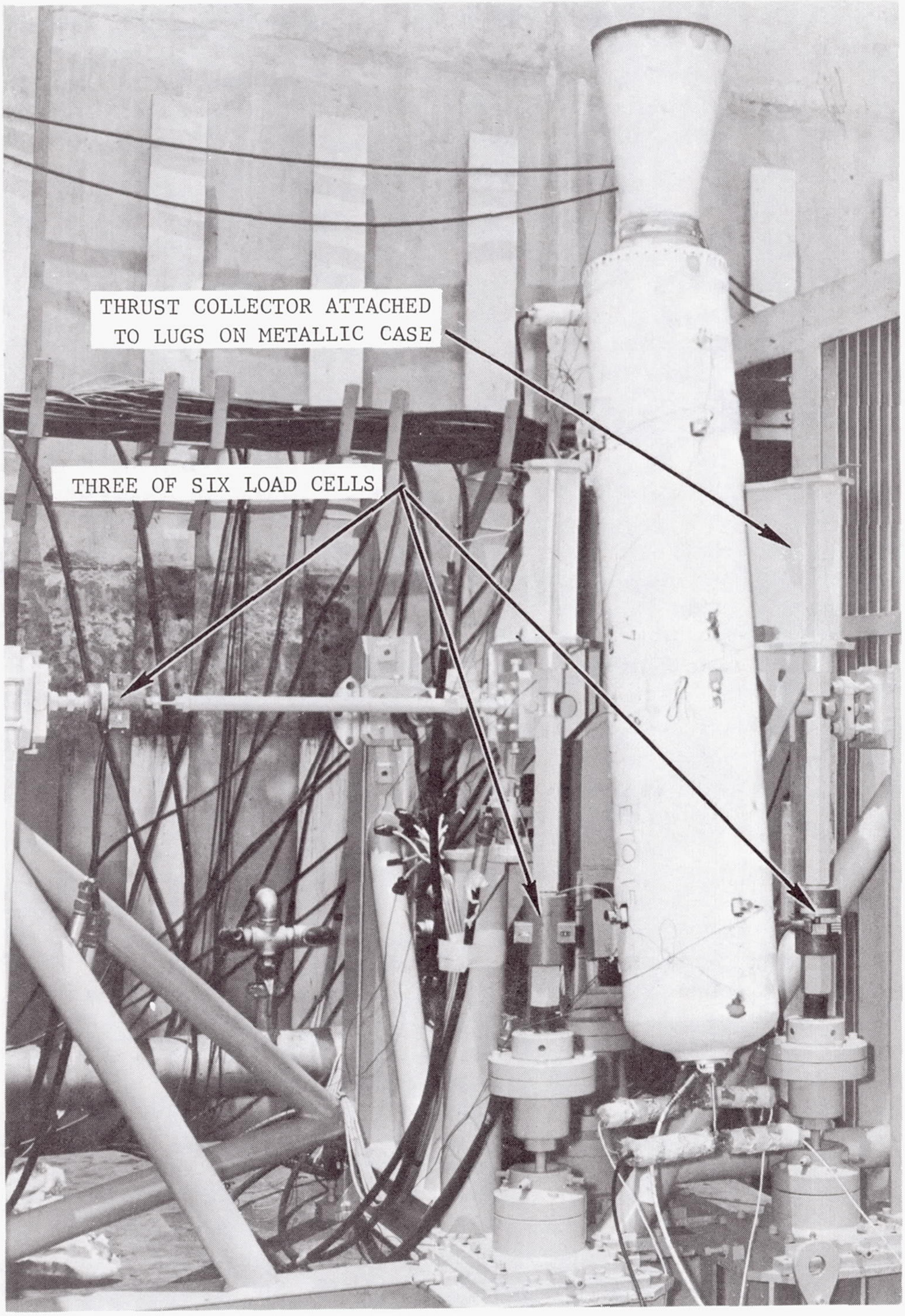


Figure 14.—Vertical six-component thrust stand.

Accurate measurement of instantaneous weight change is desirable so that instantaneous specific impulse may be determined, but such a measurement is beyond the state-of-the-art for tests that involve side loads from movable nozzles. Additionally, personnel at almost all test sites consider that such a measurement is beyond the state-of-the-art for tests with fixed nozzles.

2.2.1.8 Motor and Stand Balance

For spin or centrifuge tests, balancing of the motor and test stand generally is necessary to minimize the occurrence of vibration that can produce inaccurate thrust measurements or cause structural damage to the motor or its attachments. However, many motors are not balanced, either because spin rates are low during testing or because motor design is symmetrical. Attachments placed asymmetrically on the motor, such as pressure transducers and cabling that spin with the motor, are recognized and accounted for when balancing motors. Requirements for allowable dynamic unbalance in measurable units, e.g., ounce-inches, commonly are not specified. The allowable dynamic unbalance of a small, lightweight motor at high spin rates is considerably less than that of a large, heavy motor at low spin rates. A medium-small space motor weighing 220 pounds is balanced to within 3 ounce-inches at 4 revolutions per second. To preclude the possibility of destructive vibrations, the natural frequency of vibration of the spin stand and motor is determined, and then used as a guide for specifying allowable spin rates. During centrifuge tests, the inert weights of the motor, attachments, and half of the propellant charge are counterbalanced (fig. 2.)

2.2.1.9 Protection From Environmental Temperatures

Environmental temperatures around the motor and thrust stand during testing often are high enough for a sufficient duration to create errors in thrust measurement unless preventive measures are taken. Load cells, flexures, connectors, and other thrust stand components are temperature-sensitive, and long exposure in confined test locations has caused appreciable heatup that has influenced adversely the accuracy of the thrust measurement. Load cells generally will record a 0.1-percent change for a 100° F temperature rise; consequently, the temperature gradient across a load cell is held to a minimum to provide the best accuracy of thrust measurement. Aft-located load cells on multicomponent test stands usually require thermal protection if they are in direct view of the nozzle exhaust plume. The forward-thrust load cell is in a relatively protected location and generally is not insulated unless the test is in a confined location that may result in appreciable convective heating.

Universal and plate flexures are usually constructed of high-strength steels and are carefully sized for the expected loads; overheating the flexures during testing decreases their rated capacity, and the prior thrust stand calibration is negated or nullified. Many tests are customarily water quenched at motor tailoff. This practice causes surface hardening or embrittlement of heated flexures, and the resultant adverse effects will be imposed upon the subsequent test unless this insidious condition is recognized and alleviated. Figure 15 shows thermal protection on a test stand, flexures, linear bearings, and cabling. The visible thermal protection is aluminum foil wrap. Underneath the wrap are two types of insulation that are used on the test stand, flexures, and linear bearings: (1) wide-tape asbestos cloth used for wrapping the vertical supports and flexures of the test stand, and (2) zinc chromate putty formed around the linear bearing located at the top of the test stand vertical support. When there are favorable test circumstances, which may include short exposure times, extensive radiant-heat shields, or an open, unconfined test area, tests are conducted without thermal protection against environmental temperatures.

2.2.1.10 Test Stand Restraints

Unrestrained motors have left test areas for short, uncontrolled flights that have jeopardized surrounding facilities and personnel. Test stand restraints are commonly employed to prevent or slow down gross motion of the motor and stand in the event of malfunction during testing. Often an isolated test location will allow deemphasis of the use of test stand restraints as a safety precaution. When restraints are necessary, various devices are employed; figure 16 illustrates several of these devices. The usual restraints are I-beams, walls, restraint blocks, struts, cables, impaling rods, and cutting bars. An aft-motion restraint block is shown in the bottom of figure 16; a forward-motion restraint similar in size and shape is mounted on the forward end of the motor not visible in the figure. Cable motion restraints and restraining walls are shown in figure 12. Impaling rods, pointed to the walls of the motor case, are shown in figure 15; impaling rods are a form of motion restraint intended to puncture or rip open a glass-filament motor chamber to inhibit gross motion in the event of malfunction.

2.2.2 Pressure

Measurement of motor chamber pressure to verify design is more common than measurement of forward thrust. However, accurate measurements are not always made. The following are typical examples of unfavorable conditions and circumstances that have been experienced:

(1) Questionable data resulted when pressures during a test rose to levels outside the range for which the pressure transducer had been calibrated.
(2) Rapidly changing pressures or cyclic pressure variations caused by oscillatory burning were not measured accurately or remained unnoticed because the response of the pressure train had been degraded by oil filling.
(3) Heat affected the pressure transducers, and data were inaccurate.
(4) The pressure path was plugged by deposits of combustion residue, and data were erratic.

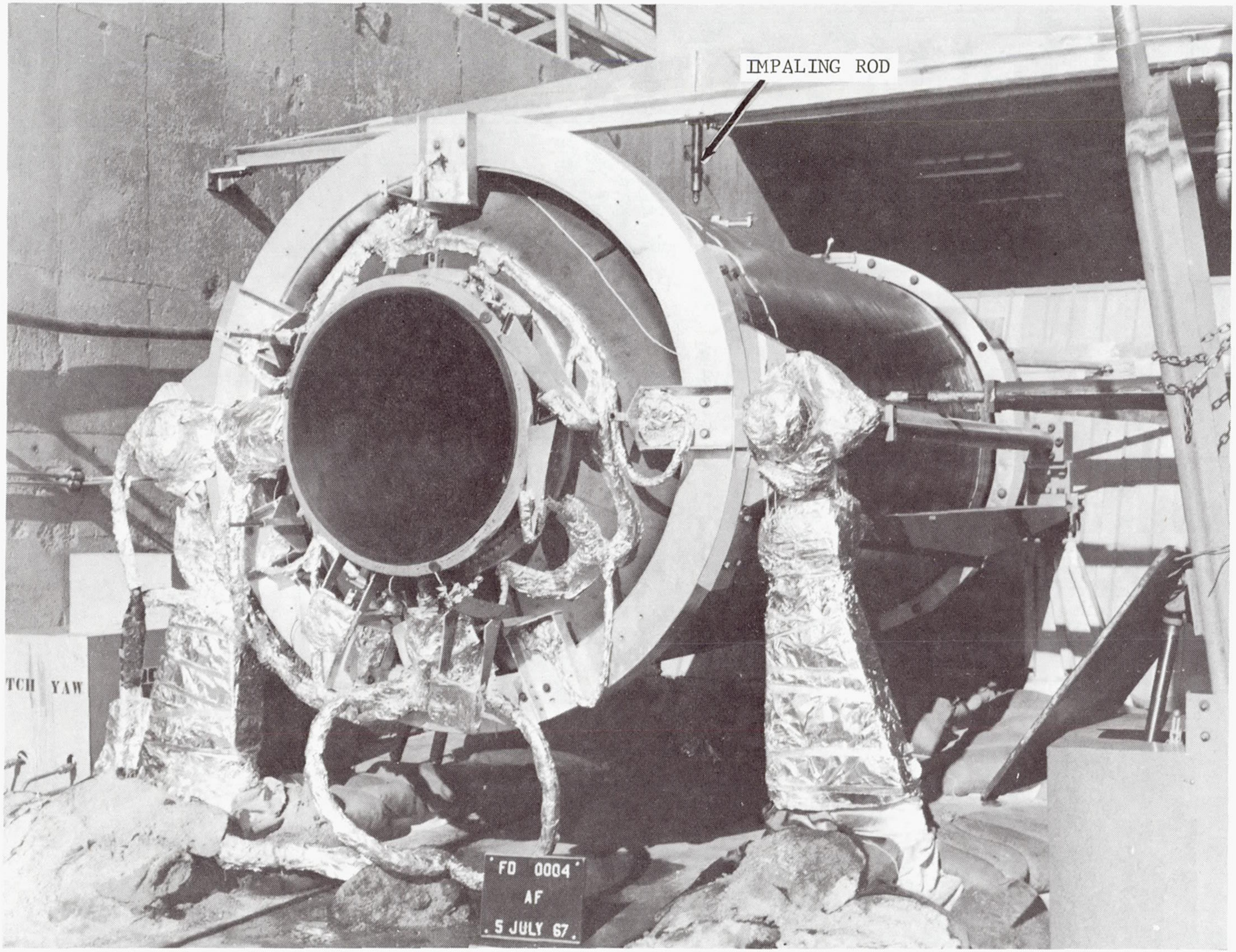


Figure 15.—Aluminum foil wrap as thermal protection on test stand, flexures, and cabling.

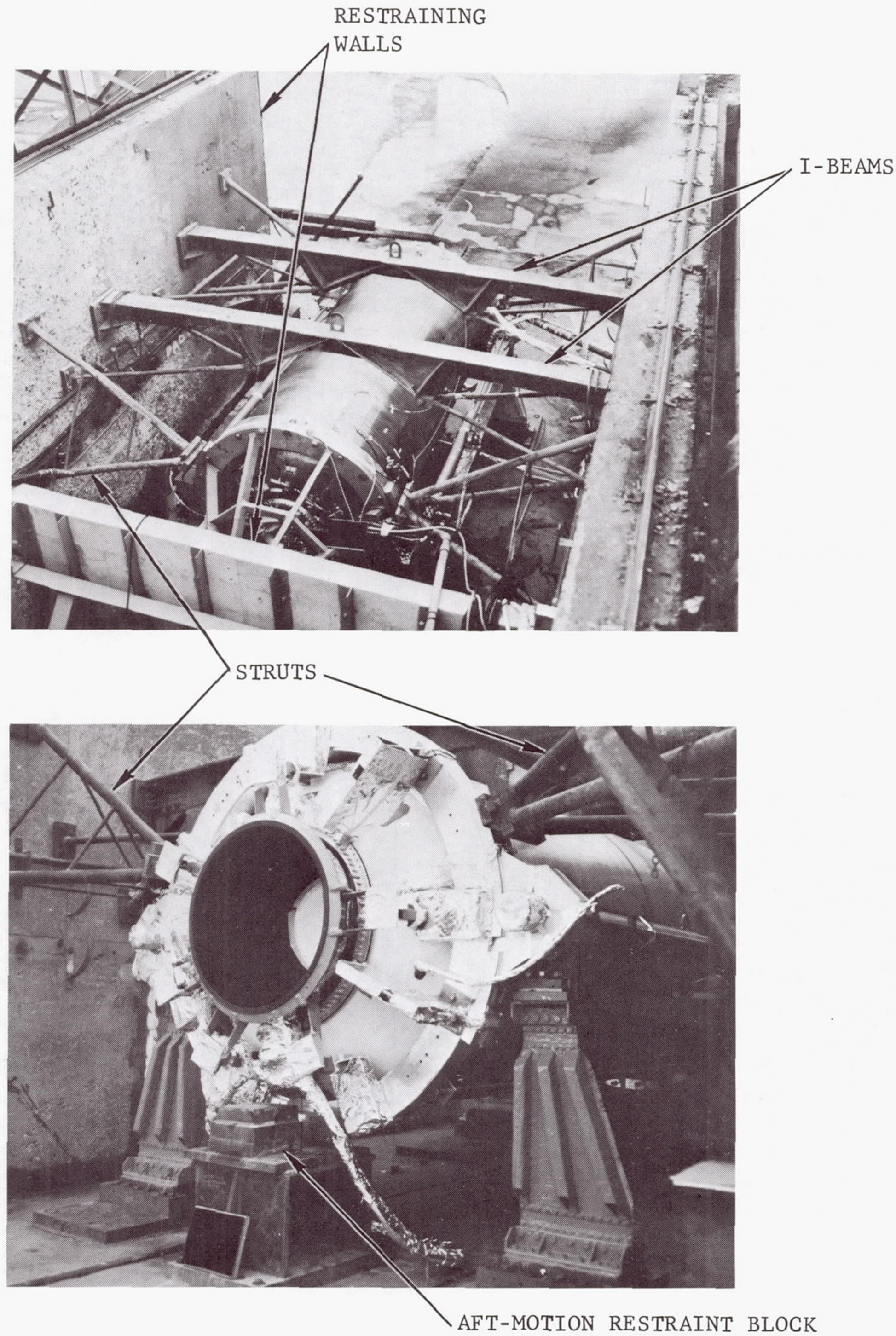


Figure 16.—Antiflight or motion restraints.

2.2.2.1 Range and Capacity

Various kinds of pressure transducers including flush diaphragm and cavity type instruments (fig. 17) are employed. Most of these yield data of varying accuracy up to about 150 percent of their rated capacity, but to yield accurate data, each should be used within its rating; common ratings are 0 to 300 psig, 0 to 500 psig, 0 to 750 psig, 0 to 1000 psig. Allowable overloads may be about two to three times greater than the maximum rating before structural damage occurs to the gage. Low-range pressure gages, 0 to 10 psia to 0 to 50 psia, are used to measure residual pressures that may occur during motor tailoff; these gages may sustain overloads up to 500 psia and higher without sustaining damage or requiring recalibration. Redundant systems are common, and dual-range monitoring provides accuracy over wide ranges of motor pressure. Igniter pressures and motor chamber pressures are sometimes monitored by the same transducer if the system permits dual capability. The common

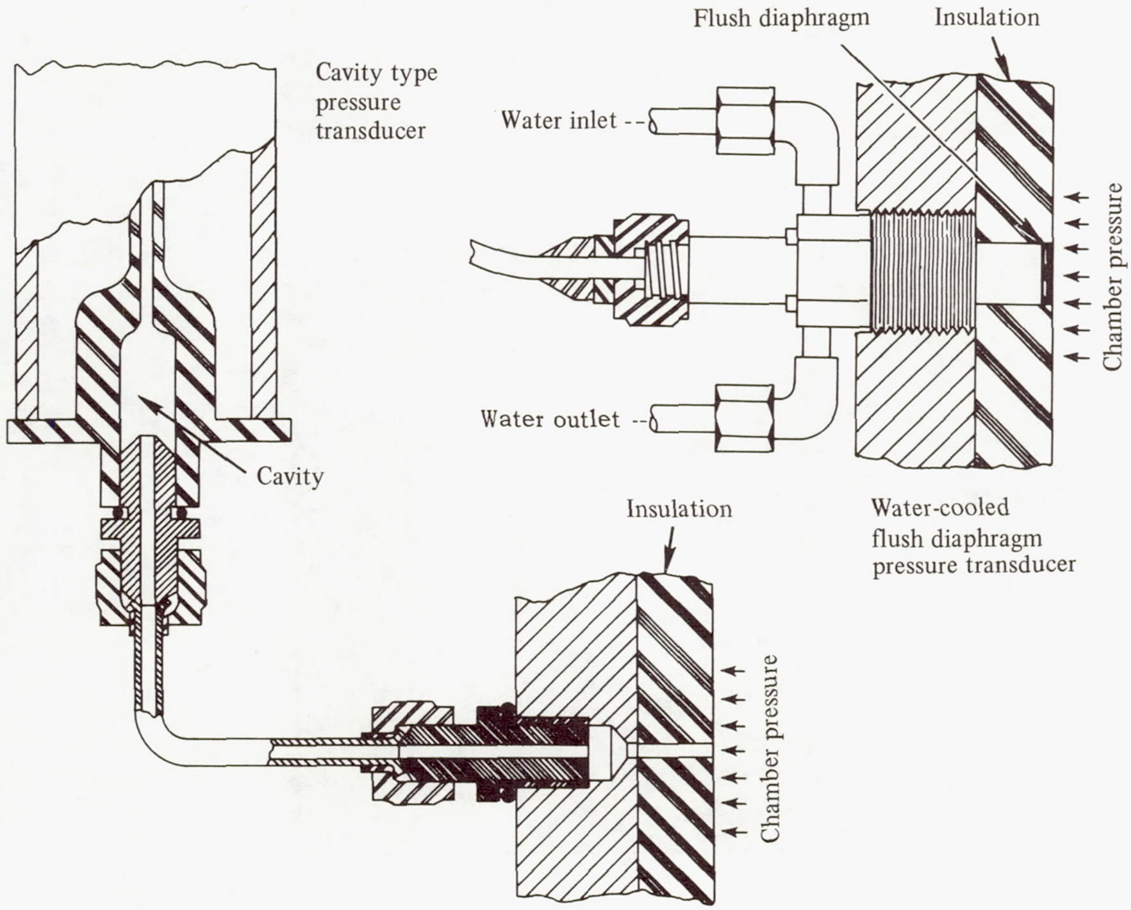


Figure 17.—Flush diaphragm and cavity type pressure transducers.

practice is to have two or more transducers monitor chamber pressure and two or more transducers monitor igniter pressure. Figure 4 shows clusters of four transducers. Transducers with a high range are common for development tests, where failure or overloads are more probable.

A cluster of high- and low-range pressure transducers used to measure pressure acurately over a wide range is shown in figure 18; the cluster is attached to an angle iron by means of high-strength adhesive tape and rubber-covered straps. Two 0 to 750 psig gages, one 0 to 50 psia gage, and one 0 to 15 psia gage are shown. The 0 to 750 psig gages were selected to measure the predicted maximum pressure of 550 psia during a development test in which a pressure overload was expected.

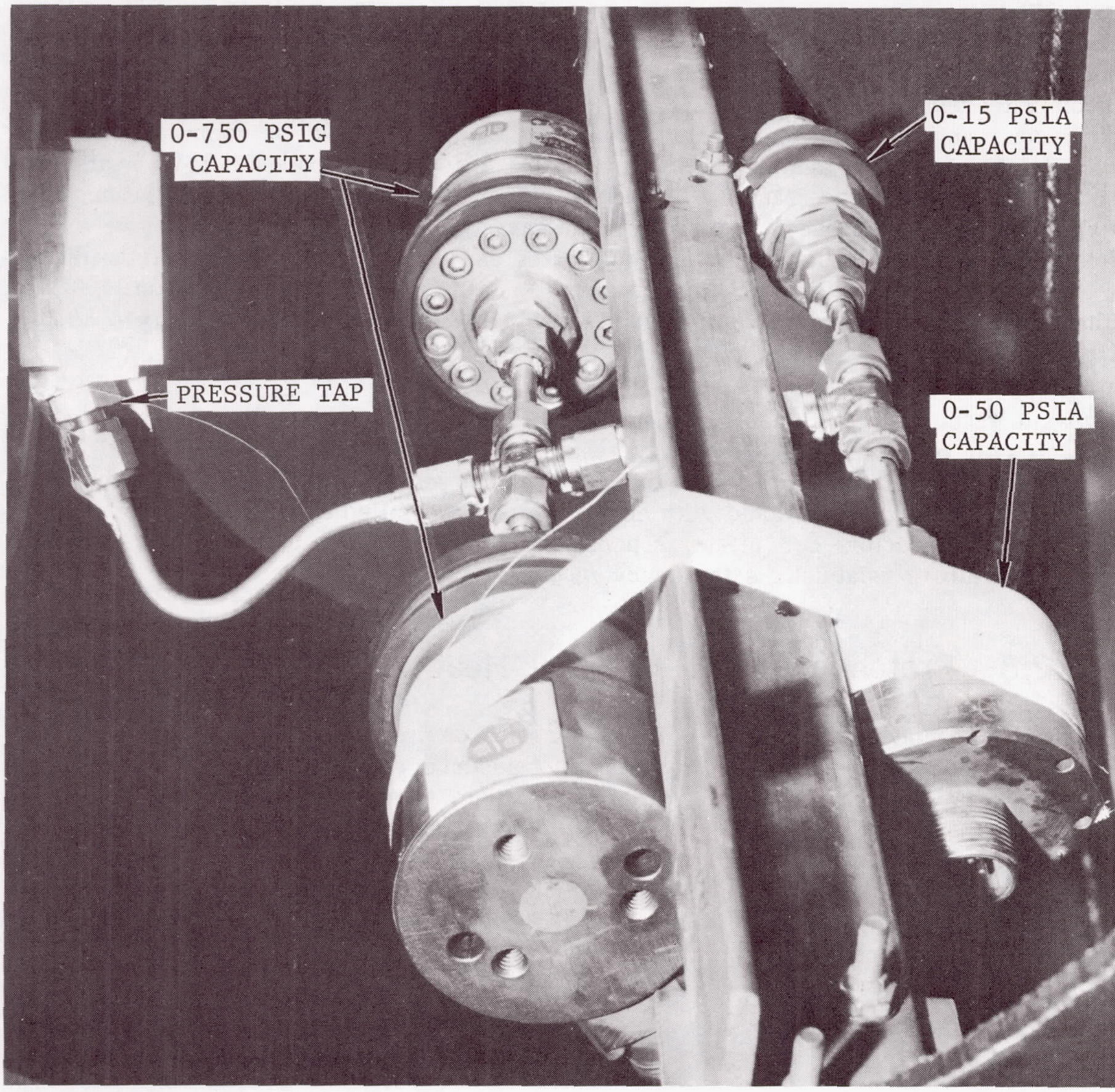


Figure 18.—A cluster of pressure transducers for measuring a wide range of pressures.

2.2.2.2 Dynamic Response

Dynamic response to rapidly changing pressures is usually dependent upon the entire pressure train and is not an independent consideration for the kind and type of transducer. The diameter, length, directional changes, and diameter changes of the pressure path as well as transducer cavity volume influence dynamic response. For example, ¼-inch-diameter tubing is usually kept to less than 2 inches in length, and a minimum number of bends and diameter changes are employed in the pressure train. Bend radii are usually larger than five times the tubing diameter. Tubing filled with silicone or fluorocarbon oil or with silicone grease is used at some test sites, while unfilled lines may be preferred at others. However, it is generally recognized (refs. 38 through 40) that filled lines degrade frequency response while providing desirable thermal insulation, and a tradeoff of these conflicting factors is usually conducted to arrive at a suitable design. Furthermore, when the tubing is filled, all entrapped air must be removed. Incomplete removal of air from filled lines has caused erratic measurements. It is common practice to place a small amount of silicone grease or room-temperature-curable rubber on the diaphragm of a pressure transducer to protect it from heat, provided the attendant decrease in frequency response of the transducer is permissible (which is the usual case). Common strain-gage-type transducers usually have a flat frequency response to about 600 Hz, but losses caused by tubing length, bends, diameter charges, and total internal volume often limit the upper response to about 200 Hz. Flush-mount transducers are employed where higher frequency response, up to 10,000 Hz, is needed.

Dynamic response requirements vary with test objectives. In development tests, transducers with relatively high frequency response are commonly used so that all likely pressure oscillations and pressure transients will be sensed. When the probable range of frequencies can be predicted with accuracy, a more limited response range is chosen. Because many factors can affect response, it is customary to calibrate the complete pressure train to establish its frequency response.

2.2.2.3 Protection From External Heat

Pressure transducers are sensitive to their external environment and often are protected by heat shields or insulation. The pressure transducers shown on figure 4 have been covered with zinc chromate putty to protect them from external heat so that their accuracy will not be impaired. As reported in reference 38, even sunshine on the transducer housing can cause a thermal gradient sufficient to produce a measurable error. For commonly employed strain-gage transducers, about a 1-percent change of measurement occurs for an increase of 100° F in the transducer temperature when it is functioning in its compensated operating temperature range, usually from about −65° to

+250° F. When transducers are placed on the aft regions of a motor in the direct view of the nozzle exhaust plume, additional insulation is applied to the transducer. Insulation materials that are suitable include asbestos-tape cloth, zinc chromate putty, room-temperature-vulcanized (RTV) rubber, and reflective aluminum foil.

2.2.2.4 Protection From Internal Heat

The pressure train heats as the igniter or chamber is pressurized by hot gases. Rapid pressurization may result in almost adiabatic compression of gases in the pressure train. Gas volumes are kept small by the close-coupling of transducers having small cavities. This practice minimizes the amount of heat absorbed by transducers and tubing. The use of oil- or oil-and-grease-filled tubing is preferred at some sites to prevent heat from influencing transducer accuracy, but other problems arise (sec. 2.2.2.2). At some test sites, silicone grease-filled transducer cavities are employed to prevent heating of transducer diaphragms. Line-of-sight radiant energy from the motor or igniter chamber creates problems when close-coupled transducers are used. A bend in the tubing (as shown in fig. 17) is utilized to prevent line-of-sight radiant heating of the diaphragm. Some transducers are designed to be water-cooled so that the effects of radiant heat can be minimized. Helium-gas-bleed transducers have been used occasionally; the helium gas bleed assists in (1) thermally isolating the sensing head, (2) keeping the pressure path from plugging (sec. 2.2.2.5), and (3) improving frequency response (sec. 2.2.2.2). Motor firing durations longer than 5 seconds usually aggravate the internal-heat problem because there is more time for heat transmission.

The critical factor of internal heat influencing pressure transducer accuracy overlaps the problem area identified in section 2.1.2.4.

2.2.2.5 Prevention of Plugging

The entrance to a pressure train is often subject to plugging by deposits of combustion residue originating in the igniter or motor chamber. Plugging has been a problem with some designs, and erratic monitoring of pressure has resulted. To avoid plugging, the entrance to a pressure train usually is located where gas velocities are low and deposition of combustion residue is unlikely. In addition, a phenolic pressure cap with several lateral holes commonly is used at the entrance to a pressure-measurement train. Small holes of less than about 3/16-inch diameter are avoided because they have a tendency to plug and result in erratic measurements. Large holes of more than about ⅜-inch diameter also are avoided because of excessive heating by hot gases. At some test sites, the use of an oil-filled pressure train has contributed to minimizing this problem. However, as noted in section 2.2.2.2, filled lines degrade frequency response and involve the risk of erratic measurements resulting from entrapped air; consequently, it is generally recognized that filled lines should be used with caution and due regard for the problems involved.

Separate and redundant pressure paths (sec. 2.1.2) are commonly employed to minimize the possibility of loss of pressure data. As backup to pressure transducers, one or more strain gages are placed on the motor case surface so that if the pressure train is plugged or closed, pressure data may be derived from the strain measured. The derived data, while valuable, are not as accurate as data obtained by direct measurement.

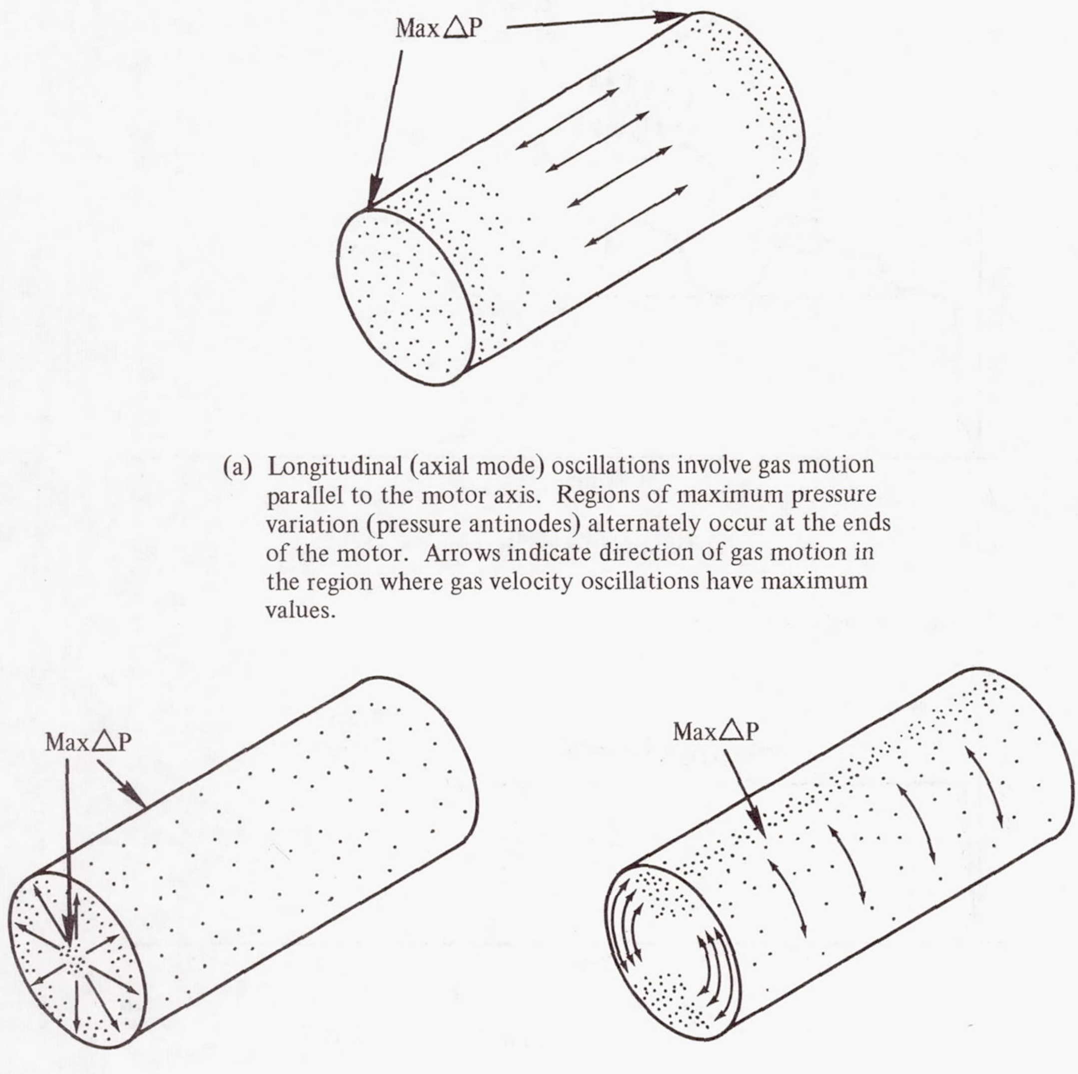
2.2.2.6 Detection of Pressure Oscillations

The occurrence of acoustic oscillations (sometimes called combustion instability) is an erratic and partially explained phenomenon observed in some tests. Longitudinal and transverse oscillations may arise in a motor chamber (fig. 19) and result in significant deviations in the propellant burning rate and consequently in the chamber pressure (ref. 41). Figure 20 shows the influence of two classes of instability on two rocket motor pressure-time histories. High-frequency oscillations up to 50,000 Hz may be present in transverse oscillations, and intermediate frequency oscillations up to 1000 Hz may be present in longitudinal oscillations; consequently, the use of transducers with the proper frequency response is essential to identifying acoustic oscillations. Fast-response miniature quartz transducers that respond only to pressure oscillation and not to steady pressures have been used to measure the amplitude of pressure oscillations exactly.

Acoustic oscillations in the motor chamber impose special problems in the proper placement of pressure transducers. Optimum placement of pressure transducers for detection of transverse mode oscillations presents a problem because the locations of the pressure antinodes move with the regression of the propellant web. The tangential mode is the most difficult to detect because of the difficulty in predetermining its orientation in the motor and the restricted distribution of the pressure antinodes. In addition, this mode may rotate in circular perforations, making the data analysis more difficult. The usual approach in choosing transducer locations is to arrange a pattern on the motor so that one location will always be near a pressure antinode.

2.2.3 Temperature and Heat Flux

Measurement of temperatures and heat fluxes during testing is commonly part of the design verification. Critical locations are monitored to confirm that temperature limits have not been exceeded on materials that lose structural strength with increasing temperature. Temperatures are measured almost exclusively by thermocouples, and heat flux by calorimeter. Occasionally, however, other less quantitative means are employed; for example, color-changing, temperature-sensitive paint sometimes is applied to motor and nozzle surfaces, and the color change is recorded by timed color photography. This simple technique is not highly accurate but is useful in locating hot spots and measuring large areas during testing. In a somewhat similar manner, infrared photographic film is employed occasionally to indicate local hot spots.



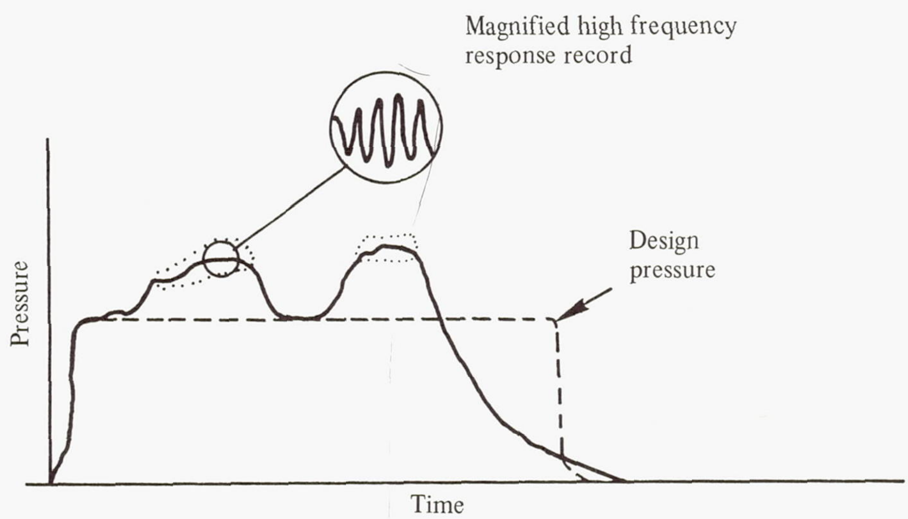
(a) Longitudinal (axial mode) oscillations involve gas motion parallel to the motor axis. Regions of maximum pressure variation (pressure antinodes) alternately occur at the ends of the motor. Arrows indicate direction of gas motion in the region where gas velocity oscillations have maximum values.

(b) Radial oscillations

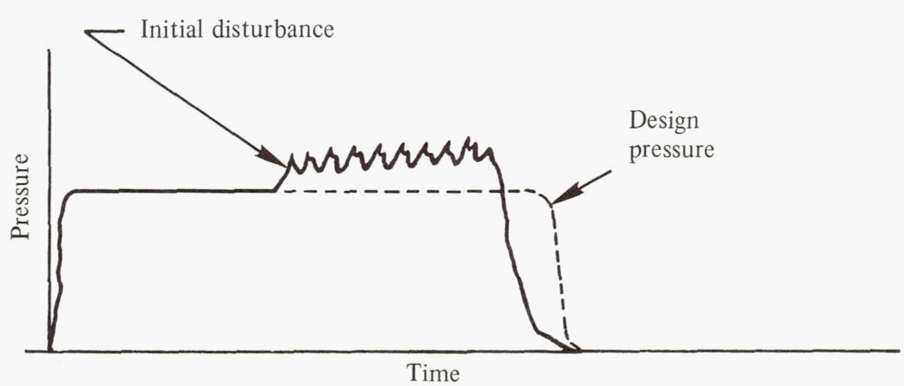
(c) Tangential oscillations

Transverse mode acoustic oscillations can occur in two basic modes. (b) Radial oscillations involve gas motion along radii as indicated by arrows. Locations of maximum pressure excursion are on the motor axis and the curved surface of the bounding cylinder. (c) Tangential oscillations involve circumferential gas motion indicated by arrows. Pressure maxima occur along lines on the cylindrical surface, which imposes stringent requirements for optimum pressure transducer locations.

Figure 19.—Acoustic oscillations that may occur in a rocket motor (ref. 41).



(a) Typical effect of instability



(b) Axial mode instability

Figure 20.—Influence of instability on rocket motor pressure-time history (ref. 41).

Accurate measurements of temperature or heat flux at precise locations are frequently required but are not always obtained. Some of the reasons for not obtaining accurate measurements are as follows:

(1) The exact positions of a thermocouple junction or a calorimeter were not known and the temperature gradients were inaccurately determined.
(2) The sensor created a disturbance of the true temperature field, and erroneous temperature readings were recorded.
(3) Temperatures and heat fluxes changed quite rapidly during testing, and measured temperature lagged true temperature.

(4) Thermocouples were placed within ablative materials, and loss of signal by an electrically conducting char layer resulted in inaccurate temperature records.

(5) Thermocouples mounted on the outside surface of a rocket motor to measure heat soak from within were influenced by exhaust plume radiation and then indicated temperatures that were not due solely to internal heat.

2.2.3.1 Range and Capacity

An unusually wide range of temperatures is associated with performance and design verification tests on solid rocket motors. Temperatures to be measured may be as high as 4000° to 5000° F, or they may be well below room temperature. Temperatures are measured by thermocouples, and proper selection of a thermocouple depends partially on the maximum temperature to be monitored. The exposure times common in rocket technology are seconds and minutes as opposed to hours, months, and years in other industries. For currently available thermocouples, the absolute maximum temperatures for the short-time exposures in rocket motor environments are

Iron-constantan	to 1500° F
Chromel-constantan	to 1750° F
Copper-constantan	to 1800° F
Chromel-alumel	to 2450° F
Platinum-10% Rh • Pt	to 3100° F
Pt • 6% Rh-30% Rh • Pt	to 3600° F
Tungsten-5% Re • W	to 4500° F depending on atmosphere

A wide range of heat fluxes is encountered during tests of solid rocket motors. Most heat-flux measurements are made on the exterior of the rocket motor; however, measurements occasionally are made inside a chamber or nozzle. Heat flux is measured by means of calorimeters of various types that are calibrated for the intended range of use; low-range calorimeters often may sustain substantial overloads (up to about 200 percent) and still yield semiquantitative data of variable accuracy. Common ranges are 0 to 10, 0 to 30, 0 to 50, 0 to 100, and 0 to 1000 Btu/ft^2-sec. Low range calorimeters are employed on the exterior of rocket motors to measure, primarily, heat flux from the nozzle exhaust plume. Calorimeters commonly are coated on their sensing surface to achieve a specific spectral absorptivity and emissivity. Often their absorptivity and emissivity are different from those of the surface being monitored. Consequently, the data obtained do not accurately represent the true heat flux absorbed by the surface.

2.2.3.2 Response Time

The temperatures and heat fluxes in critical locations on solid rocket motors usually are transient and, consequently, quick-responding transducers are desirable; however, this consideration may be secondary to the need for mechanical ruggedness for many test conditions. Quick-responding thermocouples, with time constants as low as 1 to 5 milliseconds, are obtained using thermocouple wire 0.005-inch diameter or less. The use of fine thermocouple wire requires extra care in handling because a fragile thermocouple assembly is very susceptible to breakage. For example, differences in thermal expansion between wires and plug material have caused breakage (ref. 42) and loss of data during testing. The response time of a calorimeter depends upon its size and operating range. Low-range calorimeters, being larger in diameter, usually have significantly longer response times (up to 1 sec) than high-range calorimeters (as short as 40 milliseconds).

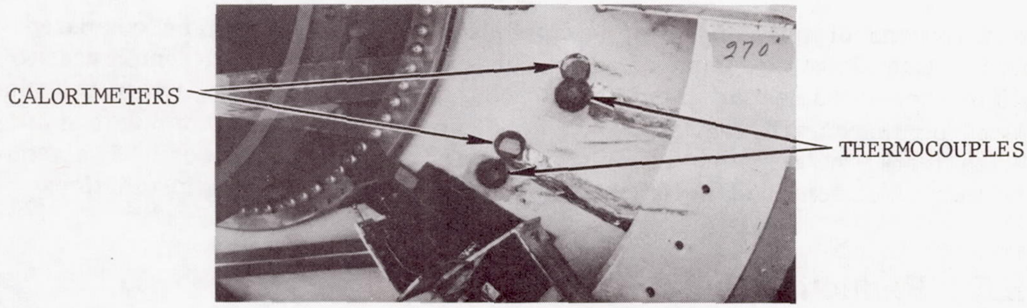
2.2.3.3 Location

Certain locations on a solid rocket motor are subject to severe localized heating and are therefore regarded as critical thermal locations. Aft-dome heating resulting from a combination of internal and external heat loads has caused test failure. Figure 21(a) shows both thermocouples and calorimeters mounted adjacent to the nozzle flange on an aft dome. The calorimeters are located to measure both radiant heat flux from the nozzle plume and convective heat flux from adjacent hot air. The thermocouples are located on the surface of the motor chamber dome to measure any heat that originates from within the chamber. Locations often are critical because the exposure time is long. Regions inside the chamber that by unpredicted events may be exposed prematurely or unexpectedly to combustion temperatures may also be critical; e.g., propellant slot regions where gas-particle velocities are high are usually identified as critical regions.

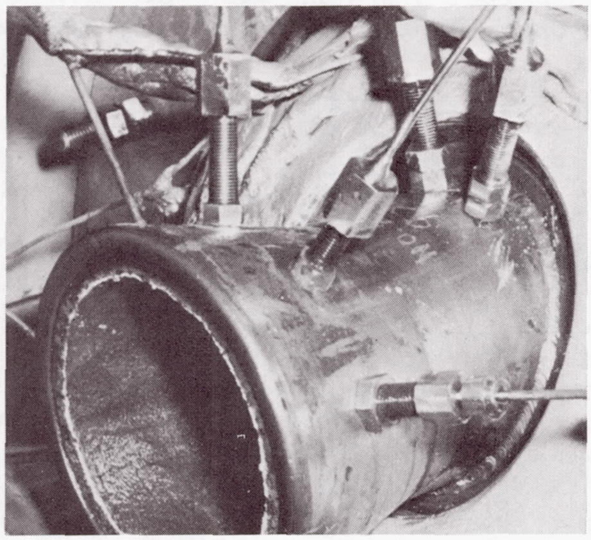
The generally recognized critical region in a nozzle is the throat region, which sustains the highest heat flux from internal heating. Figure 21(b) shows in-wall thermocouples to measure temperatures in a nozzle at various locations. Depending on conditions, other nozzle regions have proven more critical at times; for example, the failure of a nozzle/chamber attach ring and the loss of a nozzle during testing were attributed to unexpected external heat flux (refs. 25 and 26). Current practice is to measure temperature and heat flux in all locations that are considered critical.

2.2.3.4 Placement

Thermocouples often are placed within the case wall, within the internal insulation, and within the nozzle wall to measure temperature distribution through the total thicknesses involved. In addition, temperatures at the outer surfaces of the combustion chamber and the nozzle frequently are monitored by use of surface-mounted thermocouples. Propellant gas temperature in the chamber or nozzle is high, often approaching 6000° to 7000° F, and case or nozzle outer-wall temperatures usually are maintained at about ambient temperature by insulation. Consequently, steep temperature gradients are established quickly after a test starts; when ablative insulation is involved, a moving char/erosion front produces very steep gradients. Accurate



(a) AFT DOME WITH THERMOCOUPLES
AND CALORIMETERS



(b) NOZZLE WITH IN-WALL
THERMOCOUPLES

Figure 21.—Thermocouples and calorimeters on solid rocket motors.

placement of a thermocouple junction is vital for proper interpretation of test results and for verification of the adequacy of insulation design; therefore, junction position depth usually is established to within ± 0.003 in. or less. The position of a thermocouple junction can be measured in a variety of ways; the most common methods are direct physical measurement and measurement on X-ray film, care being taken to minimize parallax errors. When necessary for verification purposes, postfire sectioning is employed. Calorimeters to monitor heat flux are also subject to position criticality, since flux gradients frequently are high, and accuracy of positioning is often a necessary requirement. When repetitive tests are conducted, transducers are placed with precision so that any differences in temperature or heat flux are not due to variations of position and, therefore, cross-test results can be compared with confidence. Occasionally, simple location gages or templates are employed to aid in placing thermocouples or calorimeters accurately. For example, when transducers are placed on the curved domes of rocket motors, a flexible metal template is aligned to a fixed mark on the dome adapter flange and laid upon the dome. The template ensures that placement will be essentially the same on subsequent installations.

2.2.3.5 Reduction of Thermal Disturbance

Thermocouples always produce a disturbance in a temperature field. Thus, the reported temperature is different from the true temperature of the monitored location (ref. 43). In internal temperature measurement (refs. 44 through 46) of ablative materials used in rocket motors, significant errors are encountered because ablative materials usually have thermal diffusivities lower than those of thermocouple assemblies. Errors of hundreds of degrees are possible unless heat conducted away from the sensor hot junction by the sensor materials is minimized. Test results have shown that these errors are reduced by using a thermocouple that has a length of bare wire in the isothermal surface or plane that includes the junction. A length of bare wire equivalent to 25 wire diameters on both sides of the junction is considered sufficient.

In materials whose thermal conductivity is less than the thermal conductivity of thermocouple wire, the heat sink effect of a large thermocouple junction bead results in measured temperatures that are lower than the true temperatures. To reduce errors caused by disturbance of junction beads, the bead diameter is usually made less than 1.5 wire diameters for butt-welded junctions and less than 2 wire diameters for other types of welds.

The amount of ablative material removed for placement of thermocouple junction and lead wires is kept as small as possible to minimize disturbance. A maximum size of 24 AWG (0.005-inch diameter) wire is used for thermocouple wire, and the holes drilled for placement of thermocouple wire are usually 3 wire diameters or less. Good thermal contact and elimination of air pockets between ablative material and wire are achieved by bonding with an epoxy adhesive or any equally suitable adhesive.

A multiple thermoplug having thermocouple junctions spaced at various depths is shown in figure 22. A 0.025-in. spacing of thermocouples usually serves to define gradients accurately; at least one thermocouple is placed beyond the greatest expected penetration of the char.

Surface mounting of thermocouples to minimize thermal disturbance is described on page 67 of reference 42. Spot-welding of thermocouple junctions to the outside surfaces of motor cases and nozzles is avoided when there is any possibility that welding will endanger the structure. Electrically and thermally conductive epoxy adhesives

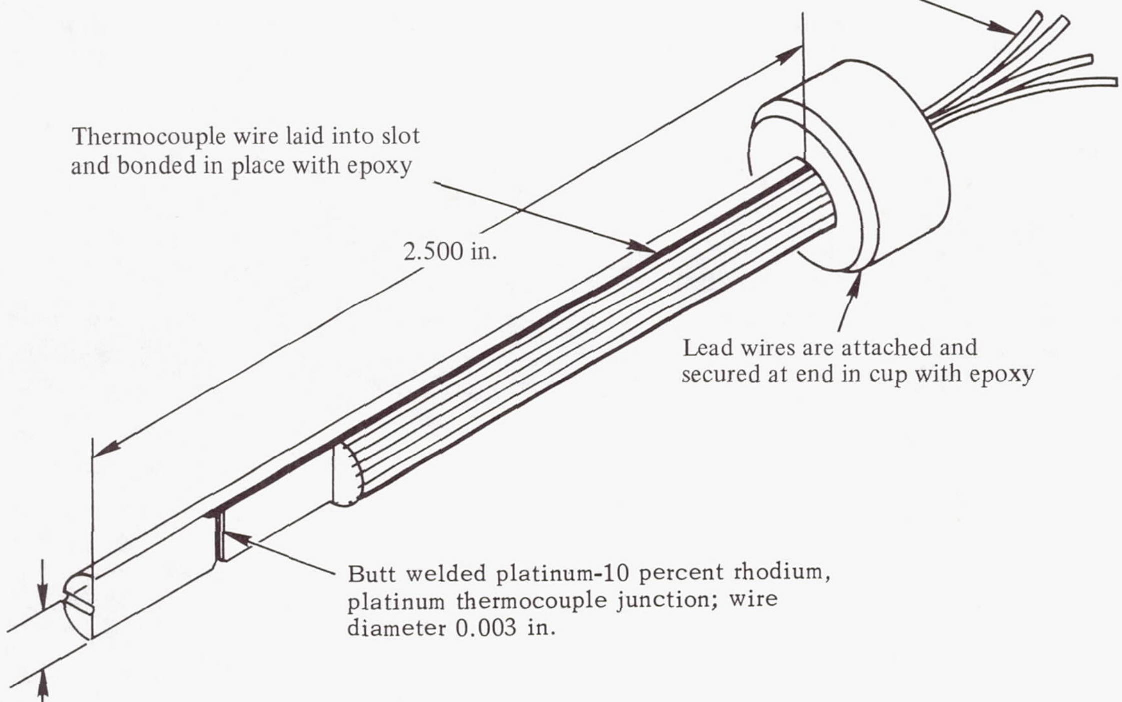


Figure 22.—Multiple thermoplug.

are commonly used to bond a thermocouple junction to a surface when the maximum surface temperature is within the acceptable working range of temperature for the adhesive. Care is taken not to allow adhesive between the surface and the thermocouple junction. Adhesive quantities are kept at a minimum to reduce thermal disturbances.

2.2.3.6 Protection From Char and Erosion

Thermocouple junctions are placed within ablative materials that are subject to char and erosion. The char layer formed by most organic ablative materials becomes highly electrically conductive as pyrolysis progresses. Thermocouple lead wires have been electrically shorted when not protected by proper insulating methods, and errors of as much as 200° F have resulted. Shorting is avoided by using a ceramic coating or tubing around the thermocouple lead wires that are not in the isothermal surface.

Erodible sandwich-type thermocouples have been used to measure the surface temperature of charred material. Two flattened thermocouple wires are insulated from each other and from the body of the unit by a thin nonconducting spacer. The resulting sandwich continuously forms a very small junction at the end terminal on the eroding surface (fig. 23). Because the isothermal plane contains little wire, conduction errors may be large (as much as 100° F for a 3000° F measurement), even with 3-mil-diameter thermocouple wires.

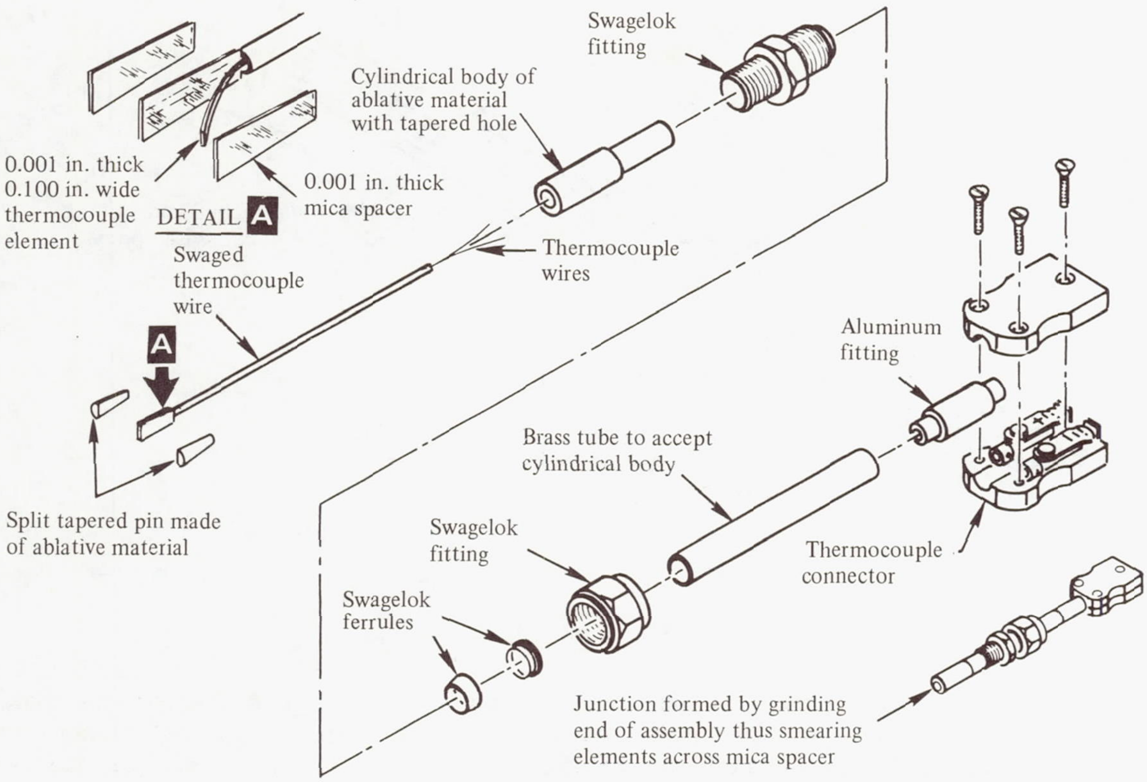


Figure 23.—Exploded view of surface thermocouple.

2.2.3.7 Protection From Radiant Heat

Surface-mounted thermocouples that are used to monitor heat soak from within the motor chamber or nozzle are often subject to radiant and external heating; protective insulation is employed to block the heat. The thermocouples shown in figure 21(a) are surface-mounted to measure heat soak from within the chamber but, because the thermocouples are on an aft dome and will be subjected to radiant heat from the plume, they have been covered by a mound of room-temperature-vulcanized rubber. (Note that the leadwires have been protected from heat by aluminum foil over a coating of RTV rubber.)

2.2.4 Strain, Deflection, and Elongation

Measurements of strains, deflections, and elongations during testing are made to verify design and to obtain data from areas that may be subjected to heavy loading or to unusual stress. Critical locations are monitored to confirm that strain, deflection, or elongation limits have not been exceeded. Photoelasticity techniques have been used in a few tests, but measurements are made by electrical-resistance-type strain gages, linear potentiometers, and linear-variable-differential transformers (LVDT). For a variety of reasons, however, the measurements are not always accurate, and data may not, in every case, be acquired throughout the testing interval. Typical problems that have been encountered are as follows:

(1) Linear potentiometers and LVDT's were exposed to deflections that were greater than their allowable shaft movement or operating range (i.e., they bottomed-out), and consequently data were missed for a portion of the test.
(2) The bonding of strain gages to cases, especially to glass-filament-wound cases, was done badly, with outright failure or partial failure of the adhesive bond resulting in loss of data.
(3) Strain gages were too large for a rapidly changing strain field; the average values of strain thus obtained were considerably lower than the maximum values in the area monitored.
(4) Strain gage grids mounted on the domes of a glass case failed because of local resin crazing; useful data were produced during only part of one test.
(5) Motor shocks imparted dynamic loads to the strain gage leadwires, and data were lost when the leadwires were whipped loose from attachment points at the strain gage.
(6) The accuracy of linear potentiometers and strain gages was degraded by radiant heat from a nozzle plume.
(7) The strain gage modulus greatly exceeded the modulus of the material being gaged (a frequent occurrence with a plastic motor component or a glass-filament composite) or the strain gage significantly reinforced the gaged structure; either condition introduced inherent errors in measurement.

2.2.4.1 Range and Capacity

Electrical-resistance-type gages customarily are used to measure strains. The rated capacity, strain range, or allowable percentage elongation of such gages depends on the geometry of the sensing grid and the elastic properties of the carrier and bonding cements. Most strain gages with flat grids longer than one-quarter inch will measure strains up to 2 percent. Gages with shorter grid lengths will measure strains of at least 0.7 to 1 percent.

Glass-filament-wound motor chambers have posed special problems because they experience greater strains than metal chambers. When chambers of the same size are subjected to the same pressure, the strains in a glass chamber may be as high as seven times the strains in a high-strength steel chamber. Hoop strains in glass chambers are as high as 20,000 micro-in./in. (2 percent); hoop failure occurs at about 3-percent strain. Axial strains are usually less than hoop strains; values as high as 11,000 micro-in./in. (1.1 percent) are observed. Axial failure occurs at about 2-percent strain. Because of the high strain levels encountered, wire strain gages are employed on glass chambers. These wire gages are constructed to measure strains of 8 to 10 percent for gage lengths of one-half inch and strains of 4 to 5 percent for gage lengths of one-eighth inch. Foil gages have limited use on glass chambers despite their advantages of smaller size, greater accuracy, and lower transverse sensitivity. Thin foil is oversensitive to extremely small areas of very high strain on the glass-filament/resin structures (primarily where the resin cracks and the strain is infinite), and foil elements in these locations break more often than wire grids.

Linear potentiometers and LVDT's (i.e., motion sensors) having definite travel lengths are used to measure deflections and elongations. Large glass chambers (15 ft long, 6 ft diameter) may experience skirt-to-skirt elongations as large as 1.7 in. as measured by motion sensors, and circumferential growths as large as 5 in. as measured by girth bands attached to motion sensors. The motion sensors are attached to an angle-iron bracket that is secured to a handling harness assembly on the test stand; the sensors measure radial growth of the motor chamber longitudinally along the cylindrical section. Girth bands that measure circumferential growth of the motor chamber during testing are shown in figure 24.

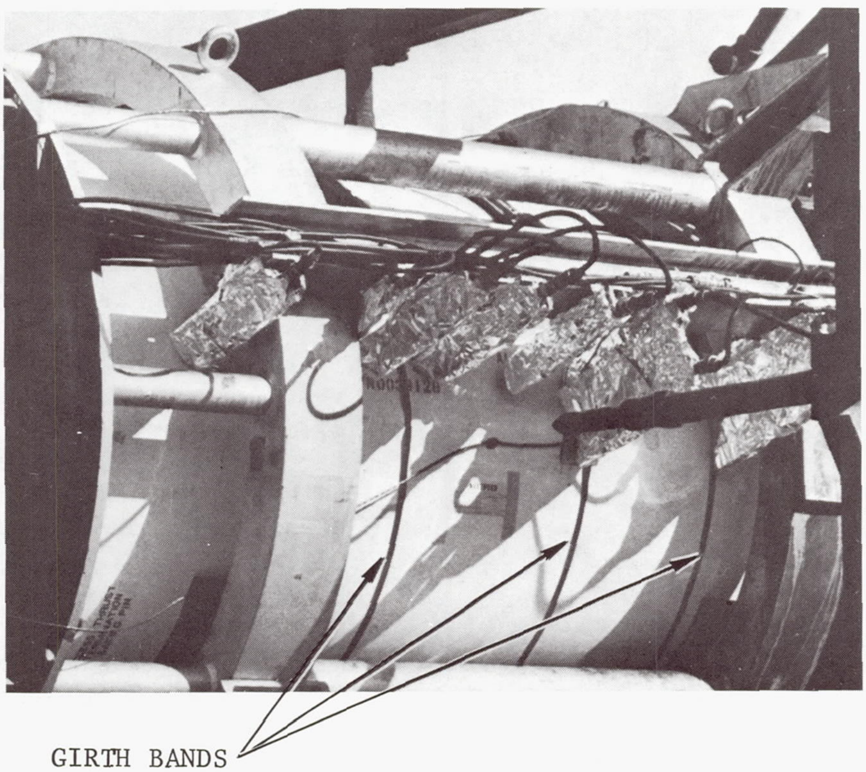


Figure 24.—Aluminum foil thermal protection on linear potentiometers.

2.2.4.2 Location

In general, critical stress locations are associated with discontinuities in thickness and shape and with the weld seams in metal chambers. Nozzle locations usually considered critical may include the motor attachment assembly and nozzle stiffening rings.

Except for motors of exactly the same design, no single location in a motor chamber is always the weak or critical location; rather, depending upon design, failures are likely to occur in a variety of locations. This is especially true of filament-wound chambers. Common locations for linear potentiometers and strain gages on a filament-wound motor chamber during testing are shown in figure 25.

2.2.4.3 Alignment

When strain data are to be used to calculate stresses, two gages are employed if the *directions* of the *principal* stresses are known. Figure 26 shows seven pairs of

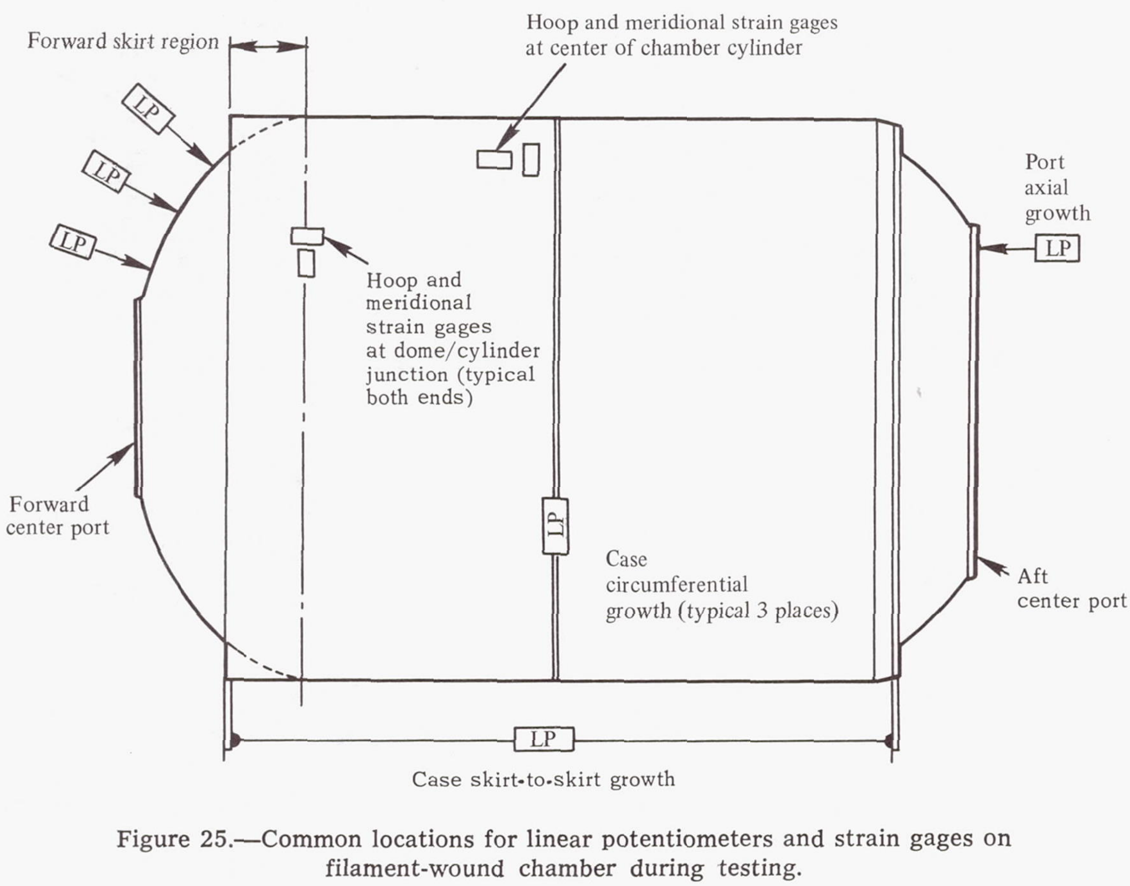


Figure 25.—Common locations for linear potentiometers and strain gages on filament-wound chamber during testing.

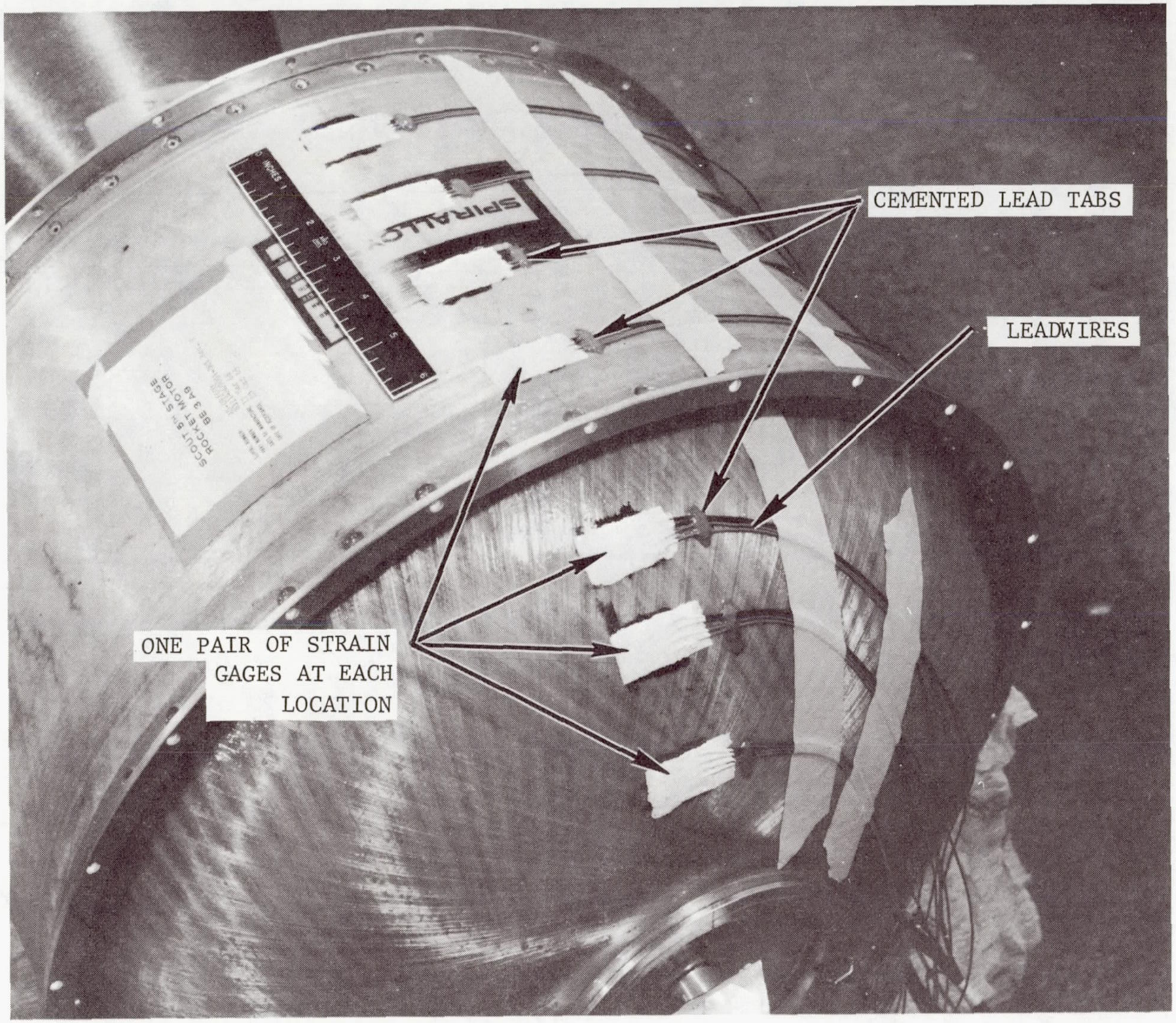


Figure 26.—Strain gages on a motor chamber.

strain gages attached to a glass-filament-wound motor chamber; each pair of gages is aligned to measure hoop and axial (meridional) strain. When the directions of the principal stresses are not known, which is a common situation, three gages are employed. This procedure permits the resolution of the principal strain magnitudes and directions; gage axes are oriented in three directions, as in a 60° delta configuration. Along the cylindrical section of a motor chamber, when bending stresses are not too high, hoop strain is much more significant than strain in any other direction. This condition makes possible the economical use of strain gages; i.e., when the directions of the principal stresses are known, two gages at a location are adequate. In some instances, a single gage is employed when the purpose is simply to monitor a location subject to unusually large strain that may lead to failure, and there is no intention to use the data for calculating stresses.

2.2.4.4 Size

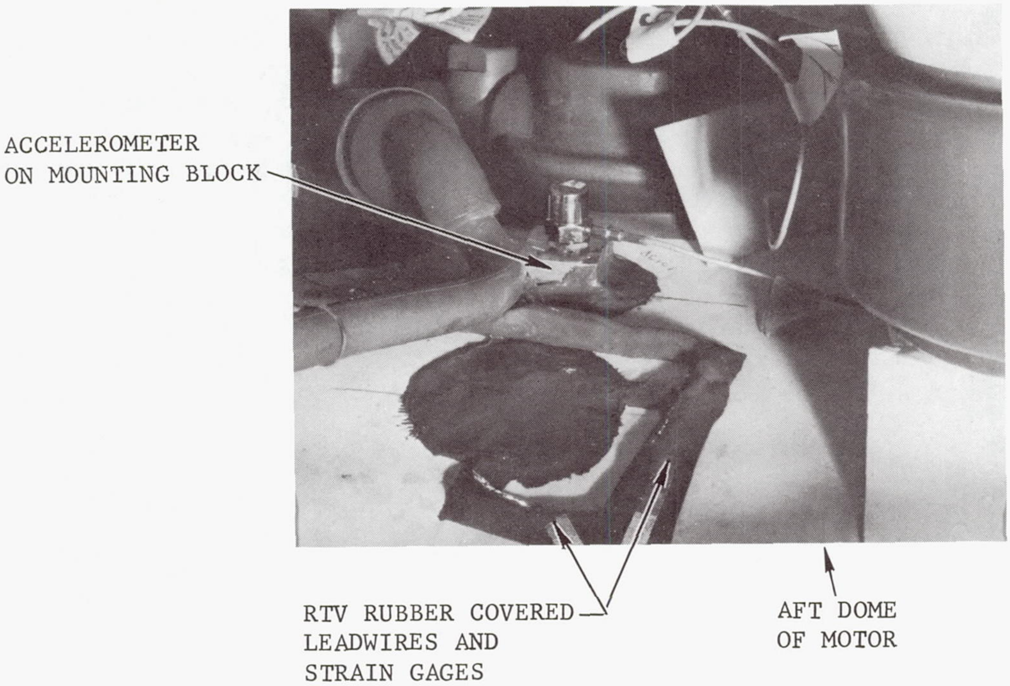
Strain gages tend to average the strains to which they are subjected, and strain fields that change rapidly with position present problems. When the strain gradient is steep, a large gage often will extend beyond the varying field; therefore, maximum strains will not be sensed, and the resultant data may be very misleading. When steep gradients are expected, small gages ranging in length from one-sixteenth to one-eighth inch are employed. Whenever possible, however, large gages (of about 1 in.) are employed because they are less expensive, require less skill for proper installation and alignment, and usually are more accurate.

2.2.4.5 Attachment

Proper installation of a strain gage by adhesive bonding is necessary for accurate measurement of strain because the basic assumption for all bonded strain gages is that the resistance change in the gage is some measure of the strain beneath it. Faithful transmission of strain from the monitored surface to the strain-sensitive filament has been difficult to achieve in practice (ref. 47). Most of the difficulty is attributed to one or more of the following factors:

- Improper adhesive
- Thick adhesive layer
- Poor mixing of adhesive
- Inadequate adhesive cure
- Poor surface cleanliness and preparation
- Inadequate adhesive elongation and shear strength
- Adhesive creep

Improper attachment of leadwires to strain gages has resulted in lost data when motor shocks separated the leadwires from the attach points. To ensure attachment of leadwires, room-temperature-vulcanized rubber has been employed in the manner shown in figure 21 for thermocouple and calorimeter leadwires and in figure 27 for strain-gage leadwires.



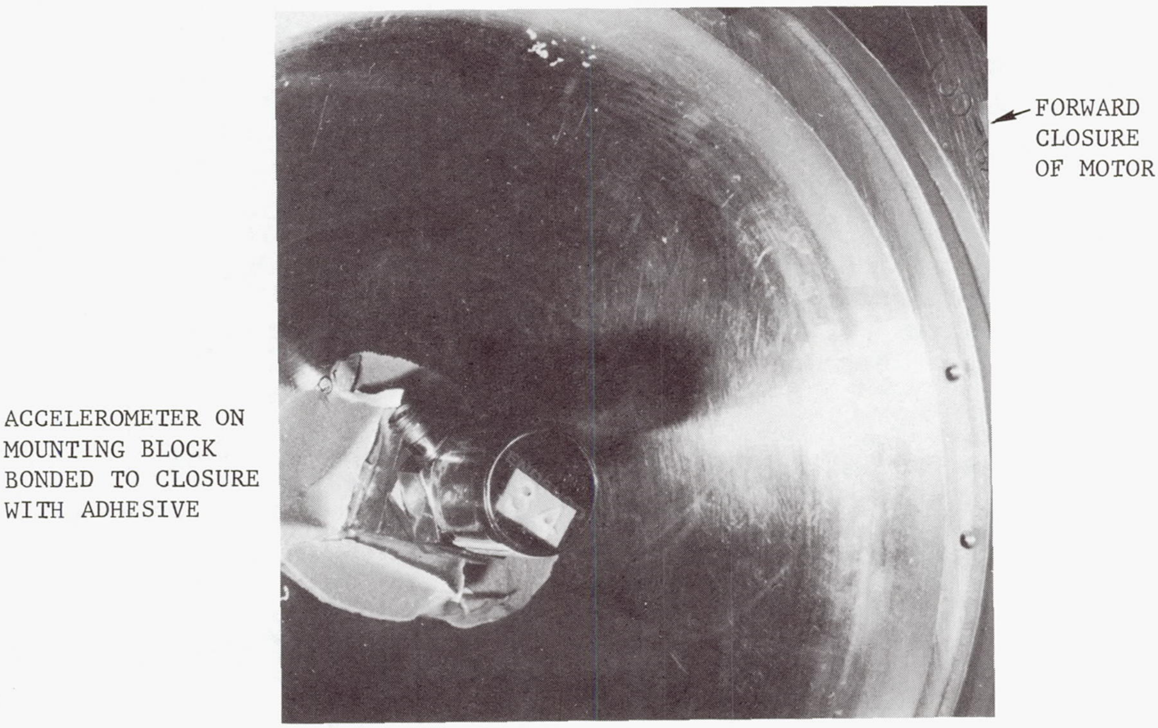


Figure 27.—Accelerometers located on forward closure and aft dome to detect acoustic oscillations.

Proper installation of motion sensors is also important in obtaining meaningful data. For example, binding of the movable shaft on a linear potentiometer has resulted in inaccurate data. Problems of binding are overcome, generally, by attaching a motion sensor so that its shaft is normal to the surface being monitored, and by preparing a smooth surface that will not hinder shaft motion in the event the surface moves obliquely in relation to the shaft of the motion sensor. Figure 24 shows linear potentiometers mounted normal to the outside surface of a motor.

2.2.4.6 Placement

Either inaccurate placement of strain gages in regions where there are strain gradients or misalignment of the strain gage with the direction of a principal strain axis can yield inaccurate data. Thus, strain gages are usually placed within 0.10 in. or less of the desired position or location. When very steep gradients are expected, placement is made with greater accuracy using smaller gages (refer to sec. 2.2.4.4). Transducers are placed with precision so that cross-test results from successive motors may be compared with confidence that differences in strains or deflections are not caused by variation of position. To assist in uniform placement of strain gages on motor chambers, simple location gages or templates (sec. 2.2.3.4) frequently are employed.

2.2.4.7 Calibration

Calibration of motion sensors and strain gages is necessary to ensure accurate measurements. Motion sensors are usually given a physical calibration; i.e., the wiper arm is actually moved (resolution of shaft motion is usually 0.2 percent full-scale or less, depending on total shaft travel). Potentiometers that have a shaft travel of about one-half inch or less will have a resolution less than 0.002 in. With LVDT's, a change in position of 0.0001 in. is readily detectable. Strain gages are calibrated electrically (not physically). Precision resistors are connected in parallel with the strain gage, and strain is simulated by a small change of electrical resistance. Strain is related to an electrical resistance change by a gage factor provided by the manufacturer; the gage factor is usually known with an accuracy of about 1 percent. To ensure an accurate conversion of the electrical signal to engineering units of strain, deflection, or elongation, electrical calibration is conducted before and after each test.

2.2.4.8 Protection From Thermal Environment

Minute changes in the electrical resistance of a gage because of changes in temperature will result in inaccurate measurements of strains and elongations. Therefore, in simulated space environments or other unfavorable environments, heat shields are often used to prevent measurement errors caused by external heating. An example of aluminum foil thermal protection wrapped around linear potentiometers is shown in figure 24.

2.2.4.9 Temperature Compensation

Strain gages often are employed on surfaces that become heated or cooled during the motor test. Since strain gages are sensitive to temperature changes, they are usually temperature-compensated to ensure accurate measurements. A beam of sunlight impinging on a gage will cause a zero shift of a Wheatstone bridge (ref. 48). False strain indications may also result from a change of electrical resistivity of the gage wire. This change may be caused either by a temperature change or by a difference in thermal expansion between the gage wire and mounting surface. To minimize thermal effects, a separate dummy (or compensating) gage frequently is employed; the dummy gage is not strained but is subjected to the same thermal environment as the active gage. This arrangement permits a separation of temperature effects, allowing measurement of strains caused by stresses. When it is impossible to subject a dummy gage to identical temperature variations, self-temperature-compensating gages, selected to match the thermal coefficient of expansion of the material being measured, are employed.

2.2.5 Shock and Vibration

At most testing locations, measurements of shock and vibration are made less frequently during testing than measurements of other motor phenomena such as thrust, pressure, temperature, and strain. The problem of measuring shock and vibration is complicated by the intense acoustic field generated during testing. Acoustic reflections off the test bay walls may excite rocket motor mechanical resonances that may not be present during a space mission (refs. 49 and 50); consequently, the usefulness of test vibration data to predict flight conditions depends on differences that exist between an actual flight and a test. When shock and vibration are measured, the measurements are usually made by piezoelectric accelerometers and by strain-gage accelerometers. Piezoelectric accelerometers require more complex circuitry and transmission lines and are more difficult to calibrate than strain-gage accelerometers. Accurate measurements by either instrument have been complicated by the following conditions:

(1) Low-range accelerometers were subjected to accelerations outside of their recommended range of operation and outside the range for which they were calibrated.
(2) Shock and vibration measurements were made at the sites where the components were located during flight but not during test; the absence of mass and stiffness provided by the hardware changed the vibrational characteristics of the region, and questionable data resulted.
(3) Limited-frequency-range accelerometers inaccurately measured both very low- and high-frequency vibrations.

(4) Poor adhesive bonding of accelerometer assemblies resulted in inaccurate data.
(5) Severe thermal environments caused a shift in the output of accelerometers, and inaccurate data were obtained.

2.2.5.1 Range and Capacity

Most piezoelectric accelerometers have an acceptable range of operation to well over 1000 g; this is above the typical values that occur during tests of solid rocket motors.

Strain-gage accelerometers are less commonly employed than piezoelectric and are suitable for use at lower g levels and low frequencies. Allowable static or steady-value over-acceleration up to 20 times the rated range is possible with strain-gage accelerometers when mechanical stops are incorporated in the instrument.

2.2.5.2 Frequency Response

The accurate measurement and characterization of shock and vibration during a test require that an accelerometer and its associated equipment possess both good low-frequency response and good high-frequency response.

Low-frequency response of piezoelectric accelerometers is limited by the electrical characteristics of the accelerometer and associated circuitry; the resistance-capacitance (RC) time constant of the accelerometer and the input impedance of the matching circuit usually result in a ± 5 percent response down to about 5 Hz. High-frequency response depends upon mechanical characteristics, which include resonant frequency or natural frequency of vibration and viscous damping of the accelerometer. When an accelerometer is undamped, response is usually flat to approximately one-fifth the resonant frequency; useful upper limits thus range from 5000 to 15,000 Hz.

Strain-gage accelerometers have lower natural frequencies than piezoelectric accelerometers; consequently, the upper limit on strain-gage high-frequency response is lower. Gages with high dynamic ranges have high natural frequencies. Typical values for strain-gage natural frequencies (and dynamic ranges) range from 300 Hz ($\pm$ 5 g) to 2900 Hz ($\pm$ 500 g). Low-frequency response is excellent, and steady values of acceleration are measured accurately.

2.2.5.3 Critical Locations

Shock and vibration usually are measured at locations associated with the following needs: (1) prediction of flight shock and vibration, (2) detection of acoustic instability, (3) measurement of test-stand dynamics, (4) measurement of motor dynamics, (5) detection of key events, and (6) verification of structural integrity.

Ordinary shock and vibration loads that are measured at the payload or at attached critical components generally are secondary considerations in motor structural design. Experience has shown that these loads are not severe from the structural standpoint of the motor.

Figure 27 shows accelerometers located on a forward closure and on an aft dome of a motor to detect possible acoustic oscillations of the chamber pressure. The accelerometers are attached to mounting blocks that are adhesive bonded to the thinnest portions of the chamber walls.

2.2.5.4 Directional Placement

An accelerometer has directional sensitivity, and its output depends on the direction of the applied acceleration; thus, the directional alignment of an accelerometer is important to ensure readings of the maximum load and overall accuracy of the accelerometer data. The shock and vibration at specific locations on a motor are often of particular interest; i.e., it may be necessary to measure the shock and vibration environment of certain hardware or electronic gear that is attached to the rocket motor. In this situation, the placement of accelerometers is determined by the location of the mounted gear. Accelerometers are placed with precision so that cross-test results from successive motors may be compared with confidence that the differences in shock and vibration are not caused by a variation of position. To assist in uniform placement of accelerometers on motor chambers, simple location gages or templates (sec. 2.2.3.4) frequently are employed.

2.2.5.5 Attachment

Improper attachment or mounting of accelerometers results in erroneous data; insecure attachment may cause large errors in the measurement of high-frequency vibration. To overcome these problems, the manufacturer's attachment procedures and recommendations for mounting torques are followed carefully.

The condition of mounting surfaces will influence the accuracy of results; i.e., an accelerometer mounted on a rough surface may be decoupled by vibratory motion. A mounting plate, jig, or fixture between the accelerometer and structure may alter or affect the accuracy of the measurement by amplifying or attenuating the real vibration. Usually, the influence of a mounting plate is carefully assessed, and the effective stiffness of the plate is increased to prevent deflection under the inertia load of the transducer mass. Adhesive bonding of an accelerometer mounting plate to a motor structure or to associated hardware is a common and convenient means of attachment. Such bonding usually is accomplished with a high-quality adhesive material that withstands shock and permits faithful transmission of shock and vibration from the structure to the accelerometer; nonhardening or solvent-drying adhesives are avoided because they act like soft springs and decouple the transducer from the test surface. Several acceptable types of adhesives are available;

low-temperature-cure epoxies or dental cements are used when environmental temperatures are low. Figure 27 shows an accelerometer on a mounting block bonded with adhesive to a forward closure of a motor.

2.2.5.6 Calibration

Proper and accurate calibration is necessary for the accurate recording of shock and vibration data. Accelerometers are calibrated to determine the ratio of output signal to mechanical input over a range of frequencies, amplitudes, and temperatures. The preferred method of frequency calibration is known as the "comparison method" (ref. 51). An accuracy of ± 1 percent is obtained by comparing the test accelerometer with the previously calibrated accelerometer or secondary standard. The test accelerometer and secondary standard or National Bureau of Standards calibrated accelerometer are mounted back-to-back with their sensitive axes coinciding on a fixture that is attached to a vibration generator, as shown in figure 28. The ratio of the outputs to the two accelerometers, together with the known frequency response of the NBS-calibrated accelerometer, gives an accurate determination of the frequency response of the test accelerometer.

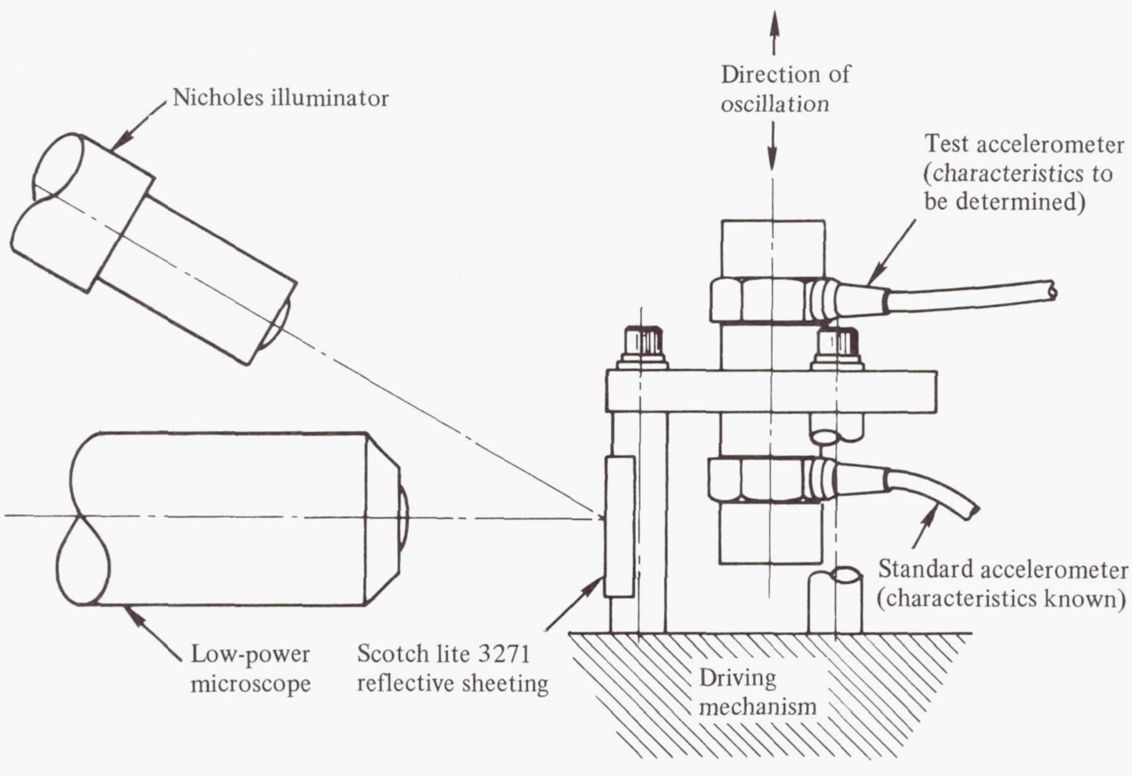


Figure 28.—Test fixture for back-to-back frequency calibration of an accelerometer.

The test fixture is carefully designed and tested to ensure that both accelerometers are experiencing exactly the same motion. Either the test fixture is one solid piece or joints are ground for a precision fit. The waveform is monitored at all times, and measurements are made only at frequencies where the waveform shows no distortion. The positions of accelerometers are usually reversed to check the accuracy of the fixture and instrumentation. After accelerometers are mounted on a motor and before testing, a simulated in-place calibration is conducted using a series-voltage insertion.

2.2.5.7 Protection From Thermal Environment

Accelerometers are sensitive to temperature changes and are protected from severe thermal environments during testing. The output of the average piezoelectric accelerometer without external cooling usually varies about ± 10 percent when used over a temperature range of − 100° to 250° F. Wide-range models that perform from − 450° to 500° F without external cooling are also available. To ensure maximum accuracy during operation at below normal or elevated temperatures, the piezoelectric accelerometers are calibrated at various temperature levels that are within their recommended temperature ranges. Temperature-compensated strain-gage accelerometers that operate over a range of about − 65° to 250° F with about a 3-percent change of output are available.

3. DESIGN CRITERIA and Recommended Practices

3.1 Design Provisions for Motor Testing

3.1.1 Measuring Thrust

3.1.1.1 Provisions for Dynamic Thrust Loads

The rocket motor and its skirts, bosses, flanges, or mounting lugs for transmitting thrust shall satisfactorily withstand dynamic thrust loads imposed by testing.

A design analysis to determine the dynamic load factor should be conducted along the lines described in reference 52. When the analysis demonstrates the need for special reinforcements or supports because of dynamic loads, the reinforcements or supports should preferably take one or more of the following forms:

(1) Stiffening and supporting rings to prevent buckling or shearing of thrust-bearing skirts
(2) Heavier and stronger skirts (for test purposes) if they are economically and physically feasible
(3) External braces and supports for flanges and mounting lugs to prevent shear, buckling, or compression failure
(4) Load-distributing pads for the motor chamber wall in the region of increasing loads
(5) Dome supports to help transmit thrust from the motor to the thrust collector if the forward dome is able to sustain the additional load (this method of support will lighten the load on the regular attachments that transmit thrust).

3.1.1.2 Provisions for Motor-Attitude Loads

The rocket motor and its skirts, bosses, flanges or mounting lugs for transmitting thrust shall satisfactorily withstand axial loads, shear forces, and bending moments related to motor attitude during testing.

It is recommended that a loads analysis be conducted to determine the load spectra on the motor for all phases of testing. This analysis should include all handling loads, loads due to motor attitude during testing, and dynamic and static loads due to the different constraints imposed on the motor by test hardware. A stress analysis of the motor should be conducted for these loads because any of them may be a critical load. For instance, in glass-filament-wound motor cases, critical stresses may occur at the joint between the skirt and the motor case. In this event, either the motor design should provide greater strength or the test method of load transfer should compensate for these stresses. The recommended practices listed in section 3.1.1.1 will alleviate critical loads due to motor attitude.

If structural and ballistic motor characteristics are likely to be affected by motor deformation due to the test setup (e.g., sag of a long motor in a horizontal position), supports should be designed to minimize the deformation. Pad-type supports are recommended, but they must permit growth of the motor during pressurization, particularly if the motor case is glass-filament-wound. In addition, the area of the supports should be large enough to minimize load concentration on the motor chamber wall.

3.1.1.3 Provisions for Spin and Centrifuge Loads

The rocket motor and its skirts, bosses, flanges, or mounting lugs for transmitting thrust shall satisfactorily withstand centrifugal and centripetal loads imposed by rotational spin or centrifuge testing.

It is recommended that the centrifugal and centripetal loads for the motor support attachments to the motor chamber be determined at the maximum test spin rate or test centrifuge rate. The loads should be added to the other loads that must be sustained and the strength requirement adjusted accordingly for the compound load of motor chamber and attachment bracket. The provisions to account for the extra load may require external motor support braces that are part of the test fixture, in addition to the appropriate reinforcements or supports listed in section 3.1.1.1.

3.1.2 Measuring Chamber and Igniter Pressure

3.1.2.1 Provisions for Dynamic Pressure Loads

The pressure path from the motor chamber to pressure transducer shall satisfactorily perform under the dynamic loads due to ignition shock (or ignition transient pressure) during testing.

Dynamic pressure loads from high-rate pressure buildup during ignition should be analyzed and assessed before final selection of a pressure path to the transducer. These ignition pressure transients should be compared to the subsequent pressure transients produced during propellant burning. When transducers are suspended from the motor by tubing, the excitation of their elastic spring-mass system should be evaluated, and any gross vibratory displacements should be eliminated by the use of support and hold-down brackets. Initial estimates of vibratory displacements can be determined from static displacements measured during pressure testing. The chamber expansions experienced by glass-filament-wound chambers, which are greater than those experienced by metal chambers, should be assessed. Tubing loops or support brackets should be utilized when necessary.

The possibility of a pressure path being closed by the deformation of elastomeric internal insulation should be assessed, and the hole diameter should be increased as necessary. If this would create an excessively large pressure path, an insert of harder, nondeforming insulation, such as reinforced phenolic, is recommended. The pressure transducer itself should sustain the expected dynamic load, and a transducer of the proper capacity and frequency response should be selected.

3.1.2.2 Provisions for Static Pressure Loads

The pressure path from the motor chamber to transducer shall satisfactorily perform under the static-pressure-induced stresses imposed during testing.

The entire pressure-monitoring train, from transducers to inside the motor, should be designed to withstand maximum pressures. Pressures during igniter action should be assessed and compared to expected chamber pressures. The pressure train, including transducer, should be proof-tested to at least peak pressures before actual use to verify the design. Leak tests on the entire pressure train are recommended to verify final installation; the leak tests may be part of other motor leak checks performed while the nozzle throat is plugged and the chamber is pressurized.

3.1.2.3 Provisions for Attachment Loads

The pressure path from motor chamber to the transducer shall satisfactorily perform under all moments and loads imposed by attached pressure tubing, support bracketry, and transducers during testing.

The loads and moments resulting from the mass of a transducer, or a cluster transducers, and the associated bracketry should be analyzed. Loads and moments that may be increased by spin or centrifuge testing should be assessed carefully. When loads are relatively light, a cluster of transducers should be supported simply with zinc chromate putty. When loads are greater, support brackets should be used to distribute the loads to avoid concentrations (fig. 4).

3.1.2.4 Provisions for Thermal Loads

The pressure path from motor chamber to the transducer shall satisfactorily withstand thermal loads imposed by testing.

Whenever hot combustion gases can enter the pressure train, the thermal loads must be carefully analyzed and assessed using conventional techniques for thermal analysis.

The internal volume of pressure paths and transducers should be minimized to reduce the quantity of hot gas that enters the pressure train. Transducers with small void volumes should be used wherever possible, and the transducer should be close coupled to the motor by short lengths of tubing whenever possible.

The use of heavy-wall stainless-steel tubing is recommended because it has greater thermal resistance than thin-wall tubing.

A silicone grease may be used as thermal protection for the transducer sensing element.

For the best pressure path design, externally cooled pressure bosses and tubing should be used except when analyses and experience with similar designs prove that external cooling is not necessary, or that the cost is prohibitive. Flush diaphragm type transducers (fig. 17) usually require water cooling.

3.1.3 Preventing Nozzle Flow Separation

3.1.3.1 Provisions for Pressure Matching

When impulse performance for a high-altitude-type nozzle is required during ground testing, a rocket motor nozzle shall not experience flow separation or jet detachment from the wall in the supersonic flow region.

Two methods are recommended to prevent nozzle flow separation: (1) adjust the nozzle expansion ratio so that the minimum expected nozzle exit pressure is not less than 0.286 $P_{environment}$, but in some cases not less than 0.4 $P_{environment}$ (refs. 5, 8, 9, and 10); or (2) reduce the environmental test pressure to simulate the environment pressure of the operational motor. When total impulse must be verified accurately for performance evaluation, both methods may be employed. If only one method can be employed, method (2) is preferred.

The test nozzle area ratio should be selected by employing the ratio of chamber pressure to nozzle-exit pressure, the ratio of specific heats, and one-dimensional flow tables.

A special test nozzle should differ from the operational nozzle in area ratio only. A test nozzle often may be obtained from the operational nozzle by machining off the unwanted length to obtain the recommended exit area ratio. Some motors are designed with nozzles that are deeply submerged into the motor chamber. Consequently, because of the proximity of the nozzle exit plane to the aft dome of the chamber, it may not be possible physically to shorten the operational nozzle. In this event, static firing at ground-level pressures with the operational nozzle should be conducted for verification of design aspects other than impulse performance, but only after assessment of the possibility of exit-cone collapse caused by pressure differences. Values for total impulse should be verified subsequently in simulated altitude tests.

When the use of special test nozzles is not desirable or possible, the environmental test pressure should be reduced to simulate the operational altitude pressure (refs. 34 and 53). A test cell is usually evacuated, and rocket exhaust gases fill an exhaust diffuser with supersonic gases, thus creating an ejector to augment the exhaust pumping system, if one is employed. Test cell pressure, $P_{environment}$, of as low as 0.1 to 0.2 psia is obtained in the most elaborate test cells (fig. 6). Testing of small motors is occasionally simplified by firing them in or into vacuum chambers. For all systems, the test environmental pressure should be carefully monitored during the test to ensure accurate conversion of the measured delivered impulse to vacuum delivered impulse.

3.1.3.2 Provisions for Pressure Variation

When impulse performance is required, fluctuations in motor chamber pressure shall not produce flow separation in the nozzle.

If the nozzle expansion ratio is to be reduced, an expansion ratio that will prevent flow separation during essentially the entire motor operation time should be used. In calculating the required area ratio, the lowest motor chamber pressure for which impulse data are desired should be employed to obtain a ratio of chamber pressure to minimum allowable nozzle exit pressure. This ratio, in turn, should be used with one-dimensional flow tables to obtain a nozzle area ratio that will permit a full-flowing nozzle for that portion of motor operation time for which impulse measurement is desired.

3.1.4 Spin and Centrifuge Testing

3.1.4.1 Provisions for Increased Chamber Pressure

The rocket motor shall satisfactorily withstand any increase in chamber pressure associated with spin and centrifuge testing.

Design analyses should be conducted to establish the increased spin sensitivity that accompanies the use of metals in the rocket motor propellant and the tendency of large agglomerates to form on the propellant surface. In addition, the analyses should account for the effect of grain design and the percentage of propellant burn surface normal to the acceleration vector as factors in producing increased chamber pressure (ref. 54). If these analyses show that pressure will increase, the motor should be strengthened to accommodate the greater stresses and to maintain the required margins of safety. Recognize that such strengthening will result in a heavier motor.

3.1.4.2 Provisions for Increased Thrust

The rocket motor and thrust-transmitting attachments shall satisfactorily withstand any increase in forward thrust loads associated with spin and centrifuge testing.

Increases in chamber pressure that result from spin testing will yield proportional increases in forward thrust. Because of the dependence of thrust on chamber pressure, the variables influencing pressure (sec. 3.1.4.1) will also influence thrust and should be considered in assessing increased loads. The higher thrust loads will be transmitted to the thrust transducer by the usual thrust-transmitting hardware attached to the motor chamber; i.e., motor chamber skirts, bosses, flanges, or mounting lugs. The design should provide for the increased thrust loads; the reinforcements or supports described in section 3.1.1.1 should be employed.

3.1.4.3 Provisions for Increased Char and Erosion

The rocket motor shall satisfactorily withstand any increase in char and erosion of the insulation associated with spin and centrifuge testing.

Increased char and erosion of internal insulation may be caused by two agents acting separately or in combination: (1) increased propellant burn rate causing premature exposure of insulation to the chamber environment; and (2) direct contact of internal insulation with liquid combustion residue (refs. 12 and 13). The severity of the increased char and erosion should be assessed as follows:

(1) The influence of the acceleration vector field on the propellant burning rate should be established by tests showing (a) the extent to which acceleration forces normal-into the propellant tend to increase burn rates, and (b) the threshold level of acceleration necessary to augment the burn rate.

(2) The relative tendency of the propellant composition to form combustion residue should be demonstrated by window-bomb combustion tests of the propellant conducted to reveal size, size distribution, and quantity of combustion residue agglomerates that form on the propellant surface.
(3) The location of potential deposition regions for liquid combustion residue should be determined by an analysis of the propellant gas-particle flow field, propellant and insulator geometry, and the burning rate of combustion residue agglomerates.
(4) The resistance of internal insulation to direct contact with the predicted quantities of liquid combustion residue and the increase in char rate resulting from the higher chamber pressure should be established by tests that demonstrate the insulation properties under these conditions.

If the assessment indicates that increased char and erosion affect structural integrity, change the insulator design by locally thickening the internal insulation to maintain an acceptable margin of safety.

3.1.5 Counteracting Combustion Residue

3.1.5.1 Provisions for Increased Char and Erosion

The rocket motor shall satisfactorily withstand increased char and erosion of internal insulation produced by slag or combustion residue resulting from incomplete propellant combustion.

Little information is available on the successful counteracting of this kind of increased char and erosion. However, use of the procedures outlined below will be helpful in defining the nature and extent of the combustion residue problem as it may affect a given design and in treating the problem once it is understood.

The motor design and propellant formulation should be compared with those of previous test motors, and the probable location and quantity of combustion residue or slag should be assessed on the basis of its occurrence in the earlier tests. Analyses based on gas-particle flow field, grain geometry, and the burning rate of metal in gas (after the metal leaves the propellant surface) should be made to determine the probable quantity of residue (ref. 55). Combustion studies such as those provided in reference 56 should be used to obtain data on burning rates of aluminum and beryllium particles discharged into hot-gas streams. Agglomerate sizes and distribution should be obtained from window-bomb combustion tests of the propellant. The flow field in the chamber should be determined, and the paths of burning fuel agglomerates should be calculated from inertia and drag laws, taking into account motor attitude and g-forces. The results of the calculation will assist in assessing impingement on motor internal surfaces. The collection of molten residue on insulator surfaces should be evaluated (ref. 57). The high erosion rates resulting from the reaction of beryllium oxide with carbon should be assessed (ref. 58). Infrared movie coverage may be employed with glass-filament chambers to verify the location of dripping molten residue inside a motor chamber (ref. 59).

If residue is a problem with a given motor, internal insulation should be added to regions where residue puddling is likely. For regions where impingement and residue collection is indicated, e.g., on igniters or submerged nozzles, collection troughs should be considered as a means for preventing drips onto internal insulation (refs. 59 and 60).

3.1.5.2 Provisions for Throat Deposition

Deposition of combustion residue on nozzle throat surfaces shall not interfere with satisfactory testing.

The possibility of deposition of combustion residue or slag on nozzle entry and throat surfaces should be evaluated by inspection of data from prior tests with identical propellant, motor, and operating conditions; as shown in reference 23, deposition predictions may be closely correlated with nozzle thermocouple response and internal ballistic performance. The time required for the oxide deposits to reach maximum thickness before melting and washoff begins should be determined by a thermal analysis allowing for heat-transfer rates, nozzle heat-sink properties, and local flame temperatures.

When designing a propellant grain and when predicting chamber pressure, thrust, and motor operating time, allow for the effect of throat shrinkage caused by throat deposition. In an extreme situation, when deposition occurs at the time of maximum chamber pressure, the deposition may be of sufficient thickness to cause a rise in chamber pressure that will jeopardize structural integrity. The structural design should provide additional strength so that the desired margin of safety will be maintained.

3.1.6 Counteracting External Heating and Cooling

3.1.6.1 Protection From Plume Radiant Heat

The rocket motor and all external motor attachments (which may include cabling, connectors, switches, instrumentation, transducers, actuators, brackets and linkage, control units, tanks, and test-stand components) shall satisfactorily withstand direct, reflected, and reradiated radiant heating from the nozzle exhaust plume during testing.

External heat loads on motor external surfaces and attachments during testing should be carefully analyzed, and design provisions should be made for their accommodation. The primary source of external heating during testing is the nozzle exhaust plume. The thermal radiation from the exhaust plume of an aluminized-composite-propellant rocket has been analyzed, and heat flux at various aft-dome locations can be predicted (ref. 61). Reradiation should also be assessed. For example, simulated altitude equipment may become hot from the nozzle exhaust plume and radiate heat back to the motor and attachments (ref. 62). The amount of radiant energy reflected from test-bay walls or floors onto the motor should be evaluated. The burn time of a motor should be considered in determining if the total quantity of heat radiated is low enough to preclude the necessity of design provisions.

When necessary, protection against heat flux from the plume should be provided by appropriate methods. Thermally reflective finishes containing reflective pigments in heat-resistant silicone-base paint may be useful in some applications (ref. 63). The use of a reflective heat shield, normal to the motor axis and around the nozzle, is recommended for blocking line-of-sight radiation. The use of a combination of wide-tape asbestos cloth covered by household aluminum foil is recommended for wrapping cabling, linkages, and test stand components (fig. 15). Aluminum foil/fiberglass batts used for insulation in home construction are recommended for wrapping test-stand components and for use against heat-shield barricades. Zinc chromate putty should be used for protecting localized areas such as transducers, cables, and actuators; in sheet form, zinc chromate putty has been applied to dome areas. Room-temperature-vulcanized (RTV) rubbers should also be considered. A double layer of external insulation for aft-dome areas is recommended. Use of water sprays to cool test-bay floors and walls should also be studied.

3.1.6.2 Protection From Plume Blowback

The rocket motor and all external motor attachments (which may include cabling, connectors, switches, instrumentation, transducers, actuators, brackets and linkage, control units, tanks, and test-stand components) shall satisfactorily withstand the heating resulting from nozzle exhaust plume blowback that may occur during motor tailoff when testing under simulated altitude conditions.

External heat loads resulting from plume blowback during simulated altitude tests (ref. 62) should be evaluated. Direct contact of nozzle exhaust plume gases on rocket motor external surfaces and attachments during the tailoff period should be accounted for. Allowance should be made for the tailoff characteristics of the motor; a fast tailoff will minimize the duration of the external heat load.

Minimizing blowback by the use of water sprays or nitrogen purging (ref. 64) is recommended (see also ref. 34). Protection against plume blowback can be provided by many satisfactory methods. A double layer of external insulation over all external motor surfaces should be used to provide complete protection; room temperature curable silicone rubber that can be troweled may be used on aft dome regions. The protective techniques described in section 3.1.6.1 may be used for the prevention of plume blowback, but added structural support for heat shields should be considered because of the blowback pressure effects.

3.1.6.3 Protection From Convective Heating

The rocket motor and all external motor attachments (which may include cabling, connectors, switches, instrumentation, transducers, actuators, brackets and linkage, control units, tanks, and test-stand components) shall satisfactorily withstand convective heating from recirculating hot gases during and after testing.

The possibility of recirculation of hot gases (ref. 65) around aft motor regions during simulated altitude tests in confined locations should be determined from results of previous similar tests and from an analysis of the geometry and clearances between exit cone and diffuser inlet (figs. 6, 8, and 9); similarly, the possibility of afterburning (ref. 66) in the test cell caused by the mixing of fuel-rich exhaust gases and air (oxygen) should be determined by analysis. The severity of the heating from each of these sources also depends to a large extent upon the geometry of the motor base and the test cell, and, as shown in reference 67, these factors should be included in an analysis of convective heating. Such an analysis should note that the flow characteristics of the hot exhaust gas leakage are also influenced by the test cell altitude. The protective techniques described in section 3.1.6.1 are recommended to protect the motor from convective heating. It is further recommended that water, carbon dioxide, or nitrogen purges be used to prevent post-test heating by combustion of fuel-rich exhaust gases.

3.1.6.4 Protection From Environmental Temperatures

Exposure of the motor and its attachments to test environment temperatures shall not adversely affect the motor performance or the test results.

Exposure to cool or warm weather before testing should be minimized; environmental cooling or heating (including wind and solar effects) may be appreciable, depending upon the season and geographic location. Temperature change should be minimized in motors that may be sensitive to a change; e.g., for many types of propellants, (1) the propellant-case-bond interfaces are severely weakened structurally when heated, (2) the propellant thermal stresses exceed allowable stresses when the propellant is exposed to wide temperature cycles, or (3) ballistic performance is affected by propellant temperature change. Temperature-controlled test bays are recommended when the added cost is justified by the need for a close control of the temperature. Removable blankets or other suitable coverings may be used to reduce exposure. Sunshades are recommended to eliminate intense solar heating of the motor before and during a test. A nozzle-throat plug or nozzle exit-plane cover should be used to protect the motor interior before testing.

3.1.7 Measuring Ballistically Related Phenomena

3.1.7.1 Provisions for Dynamic and Static Pressure Loads

The signal train from the sensing element to the receiver shall perform satisfactorily under all dynamic and static pressure loads imposed on it during testing.

As in the procedure for selecting a pressure path (sec. 3.1.2.1), no instrument or attachment involved in measuring ballistic phenomena should be used without first analyzing and assessing the loads that will affect it. Ignition shock may be the worst dynamic load, but should be compared to subsequent transients. Transducers and cabling suspended from the motor should be suitably supported to eliminate gross vibratory displacements caused by motor chamber expansions or displacements. Pressure fittings should be designed to withstand maximum chamber pressures. Brackets should be designed to sustain all dynamic and static loads imposed by the signal train and attached transducers.

3.1.7.2 Provisions for Attachment Loads

The signal train from the sensing element to the receiver shall perform satisfactorily under moments and loads imposed during testing by attached cabling, support bracketry, and transducers.

The loads and moments from support bracketry, cabling, and transducers that are attached to a motor should be carefully evaluated and added to the chamber loads for design purposes. The recommendations in section 3.1.2.3 are also applicable here. Often, simple provisions are adequate, but when attachments are numerous and heavy, load-distributing pads should be used to avoid load concentrations.

3.1.7.3 Provisions for Thermal Loads

The signal train from the sensing element to the receiver shall perform satisfactorily under thermal loads imposed by testing.

The influence of pressure forces on heated lead wires or sensors that have been embedded or inserted in the motor should be carefully assessed by thermal and structural analyses, e.g., (1) heat conduction along lead wires and into the adjacent material should be determined using the methods described in reference 43, and (2) the allowable loads and structural margins of safety should be determined for all load-bearing regions that become heated during testing. Positive retention devices should be employed to ensure that wires are not displaced by chamber pressure (fig. 11). To ensure that structural integrity will not be influenced adversely, thermal degradation of adhesive bonds should be carefully evaluated by comparing the results of the thermal analysis with the known elevated-temperature properties of the adhesive. When analysis is difficult or properties are not available, proof testing in a simulated environment prior to a motor test is recommended.

3.1.8 Measuring Other Phenomena

The signal train from the sensing element to the receiver shall perform satisfactorily under all loads imposed by testing.

The recommended practices of section 3.1.7 are applicable and should be followed to ensure that structural integrity will not be jeopardized.

3.2 Equipment and Procedures for Monitoring Motor Phenomena During Testing

3.2.1 Thrust

3.2.1.1 Range and Capacity

The capacities of load cells, flexures, and linkages shall be adequate to measure the range of loads anticipated during testing.

Load cells should normally be selected to operate in the upper 75 to 80 percent range of their rated capacity. Allowance should be made for any thrust spikes that are likely to occur so that the load cell does not suffer mechanical failure or sustain a permanent set.

Two load cells may be employed in series for more accurate monitoring of dual-range thrust, but note that this will produce a softer system with more total deflections. In other instances, dynamic response to motor thrust transients may need improvement, and a load cell with a larger-than-normal range may be selected to achieve less deflection and present a stiffer system.

Select the main thrust flexures such that their capacity is about three times the expected maximum thrust. When selecting flexures for vertical stands, add the mass of the motor and stand to the load from the expected maximum thrust. When dynamic considerations are important, use flexures with capacities up to five times expected maximum thrust. When sizing transverse flexures, take into account system mass as well as steady and dynamic side forces, thus providing improved stiffness.

3.2.1.2 Dynamic Response

The thrust stand and train shall have a dynamic response to motor thrust transients and side loads commensurate with those expected during test.

Load cells should be selected with dynamic response adequate for the expected transients. To obtain the most accurate data on thrust transients, thrust stand mass generally should be made as small as possible and system stiffness as great as possible. To decrease thrust adapter weight, structural members that offer the greatest moment of inertia for a minimum area should be used (fig. 12). Maximum stiffness is obtained by keeping total deflections or strains to a minimum. To minimize strains, low deflection load cells should be employed. Additionally, all mechanical joints should be locked to preclude serious dynamic force distortion and inaccurate static force measurement (ref. 68). For best results, a load cell should be either flanged or of male stud construction. Flanges permit accurate loading of a load cell and prevent looseness or "slop" in the thrust train when it moves from tension to compression. A split-nut locking mechanism is desirable for use with male studs to prevent motion in threaded joints. Figure 29 shows a universal flexure between a thrust buttress and a load cell; the load cell is locked to the universal flexure by means of socket-head bolts.

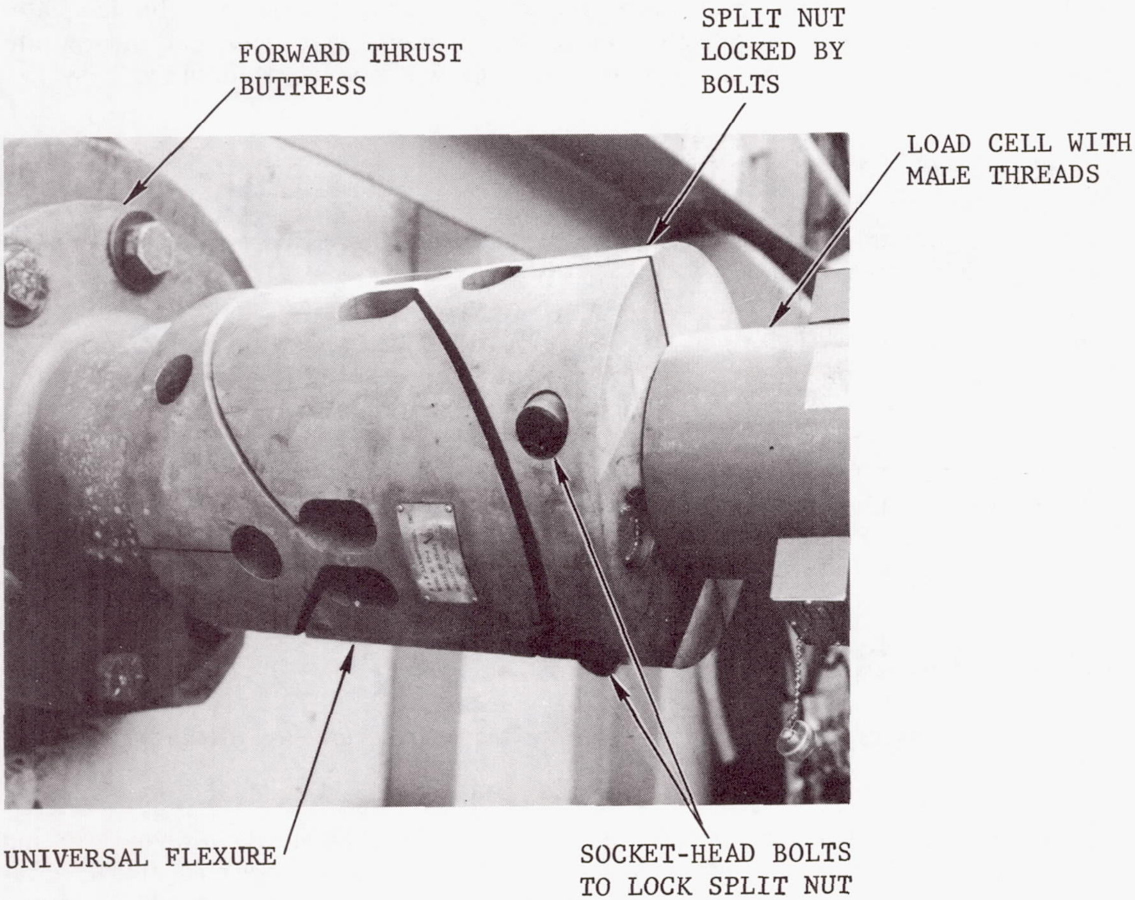


Figure 29.—A universal flexure with split-nut locking mechanism.

As a general rule, the natural frequency of mechanical vibration of the test stand and motor should be such that their time period is less than one-fourth the time period of the thrust transient from the motor (ref. 69).

3.2.1.3 Test Stand Alignment

The motor and test stand alignment shall be adequate for test requirements.

Accuracy requirements for alignment vary considerably. For maximum accuracy, an optical alignment scope with illuminating light should be employed in conjunction with a telescopic transit square. Temperature equilibrium is needed for maximum accuracy, and the alignment should be made when all components are at the desired temperature level. Permanent alignment targets or scribe lines should be located for ready reference after the motor and stand are installed. When lower accuracy is tolerable, a careful line-of-sight alignment may be employed. Such an alignment may be adequate, for example, on a simple, single-component thrust stand if it does not incorporate universal flexures and if measurement of side loads will not be required.

3.2.1.4 Test Stand Calibration

Test stand calibration shall be adequate for accurate determination of the stand losses and linkage interactions.

The test stand should be calibrated with the motor installed and with deflections on all critical linkages the same as the deflections that will occur during an actual captive-fired test. A simulated thrust load, accurately measured by a load cell, should be applied at test temperature if maximum accuracy is desired. Calibration before and after each test firing should be conducted to achieve maximum accuracy. Either a stand deflection versus applied force measurement method (ref. 70) or a deadweight calibration method should be employed. If a deadweight calibrator is used, the manufacturer's instructions should be followed carefully.

3.2.1.5 Test Stand Transverse Vibration

Thrust vector forces shall not cause excessive transverse vibration of the test stand and motor.

Thrust vector forces or any other side forces should be applied slowly to avoid exciting the mass of the test stand and motor and thereby causing transverse mechanical vibration (ref. 71). Transverse natural mechanical vibration frequencies should be determined. Any side or nozzle thrust vector loads should be applied at a rate different from the natural frequency. Adequate restraint to transverse motion should be provided by the test stand and all flexure linkages and structural members (fig. 14).

3.2.1.6 Motor Growth

Test stand design shall provide for motor growth during testing.

The test stand design should incorporate a means of permitting unrestrained motor growth during testing (ref. 11). Longitudinal growth of the motor should be permitted by using low-friction linear bearings, sleeves, wheels, or other suitable methods providing low longitudinal restraint and high transverse restraint. When necessary, transverse flexures should be misaligned a predetermined amount before the test so that orthogonal support will be provided when the motor grows during testing.

3.2.1.7 Motor Weight Change

Thrust determination shall account for the change of motor weight during testing.

The influence of motor weight change on the accuracy of thrust data is less critical during horizontal firings than during vertical firings. The ratio of weight change to thrust is an important consideration in evaluating magnitudes of possible errors; when the ratio is large, errors may be large. During vertical tests, the influence of weight change on thrust should be compensated for analytically and may be programmed into data reduction by adding algebraically the predicted instantaneous weight change to the measured instantaneous forward thrust value. During horizontal tests, the inverse pendulum effect should be minimized to decrease the influence of weight change. Reference 72 presents a method recommended for accounting for weight change of a motor when six-component force measurements are made.

3.2.1.8 Motor and Stand Balance

For spin tests, the test stand and motor shall be statically and dynamically balanced. For centrifuge tests, the motor and attachments shall be counterbalanced.

For spin tests, attachments to the motor such as pressure transducers, cabling, etc. should be balanced with the motor. It is preferable to balance the rotating parts of the test stand first and then balance the rotating parts of the test stand and motor together. Balancing should be done at approximately the same spin rate that will be used during testing. The specified allowable dynamic imbalance should not be exceeded. The frequency of natural mechanical vibration of the spin stand and motor should be determined to serve as a guide for permissible spin rates to preclude the possibility of destructive vibrations.

For centrifuge tests, counterweights should be located on the opposite boom to balance the weights of the motor and attachments (fig. 2). All of the inert weight plus one-half of the propellant charge weight should be counterbalanced.

3.2.1.9 Protection From Environmental Temperatures

Environmental temperatures during firing shall not endanger high-strength connections, transducers, flexures, or the test stand.

Load cells, flexures, connectors, and test-stand components should be protected from test environmental temperatures by suitable heat shields and insulation that will not influence test results. Confined test locations, such as simulated altitude chambers, may require that the entire test stand be protected. Many relatively inexpensive insulation materials can be used; these include asbestos-tape cloth, aluminum foil/fiberglass batts, zinc chromate putty, and room-temperature-vulcanized rubbers.

3.2.1.10 Test Stand Restraints

A malfunction during test shall not result in motion of the motor that endangers personnel or facilities.

For maximum protection, the strength required for complete restraint of motion should be determined on the basis of the maximum load (defined as the product of motor cross-sectional area and maximum chamber pressure). When less protection is permissible, e.g., when the test site is isolated or when there is less inherent hazard, restraints should be capable of slowing a moving motor appreciably. The recommended restraints are one or more of the following: I-beams, walls, restraint blocks, struts, cables, and impaling rods. A variety of motion restraints is shown in figures 12, 15, and 16.

3.2.2 Pressure

3.2.2.1 Range and Capacity

The capacity of a pressure transducer shall be adequate to measure the range of pressure anticipated during testing.

Pressure transducers normally should be selected to operate in the upper 20 to 25 percent of their rated range or capacity; this applies to both igniter and chamber pressure transducers. Expected pressure spikes should be identified and characterized so that the transducer does not sustain mechanical failure or take a permanent set.

Pressures up to 150 percent of the rated capacity of a transducer usually are safe, depending on the gage type, and will not cause mechanical damage but will introduce error because of operation in an uncalibrated region. For maximum accuracy, the transducer should operate at 95 to 105 percent of its rated capacity. The common and recommended practice is to employ two or more transducers for each pressure outlet from the rocket chamber to achieve redundance and assure accurate measurement of pressure. This is ordinarily accomplished with the use of a tee fitting.

3.2.2.2 Dynamic Response

The pressure train shall have a dynamic response consistent with the rate changes of pressure expected in the test.

Dynamic response requirements, including the necessity of measuring possible high-frequency acoustic oscillations, should be evaluated carefully. Components of the pressure train then should be selected to fit the known needs. To achieve a high dynamic response, the pressure path or pressure tubing should be as short as possible, be constant in diameter, and have a minimum number of bends or turns. Bend radii should be greater than 5 tubing-diameters. Heavy-wall, ¼-inch diameter, stainless-steel tubing less than 2 in. long is recommended. Whenever highest frequency response is required, flush-mount transducers should be used. Helium-gas-bleed transducers should be considered because they may offer advantages, for a specific design, in obtaining high-frequency response.

Pressure paths generally should not be oil-filled (ref. 39), unless circumstances involving heat blockage warrant the use of oil or grease. As noted previously, erratic and degraded frequency response has been reported (ref. 38) when filled lines were used. If a filled line must be used, all air must be excluded from the line, even though this is often difficult to accomplish.

The entire pressure train should be calibrated to ascertain frequency response (ref. 40) when required.

3.2.2.3 Protection From External Heat

Environmental temperatures shall not impair the accuracy of the pressure transducer.

Pressure transducers should be protected from environmental temperatures by one or more of many suitable insulation materials; e.g., asbestos-tape cloth, zinc chromate putty or seam-sealing compound, RTV rubber, and aluminum foil (fig. 4). When pressures are monitored at both ends of a motor, the aft-mounted transducers generally should be given more protection because they operate in a more severe thermal environment. When environmental temperatures are unknown and maximum accuracy is necessary, the temperature rise of a transducer should be measured and pressure measurements corrected for the rise in temperature.

3.2.2.4 Protection From Internal Heat

Heat from the motor chamber or igniter shall not impair the accuracy of the pressure transducer.

The use of short pressure paths having small internal volumes to minimize the quantity of hot gas is one method of protecting the transducer from excessive heat originating in the motor. Transducers having small cavities also should be utilized if possible. Heavy-wall stainless-steel tubing has greater heat-sink capability than thin-wall stainless-steel tubing and is recommended for most applications; however, where high strength is not a requirement, copper tubing may be used successfully. Depending upon installation, close-coupled transducers may require the blockage of line-of-sight radiant heat to the sensing element; an elbow or bend in the tubing is recommended for this purpose. A small amount of silicone grease or room-temperature-curable rubber on the diaphragm of a sensing element is recommended for thermal protection; however, the transducer frequency response will suffer. Consequently, this practice is not recommended when maximum frequency response is needed. An external cooling system is recommended for severe conditions encountered by flush diaphragm transducers (fig. 17). A helium-gas-bleed transducer may be useful in providing improved thermal isolation.

To minimize the influence of heat on the accuracy of pressure measurement, temperature compensated pressure transducers should be used within their specified range of compensation, and the influence of heat on the transducer accuracy should be measured accurately by test.

3.2.2.5 Prevention of Plugging

The pressure train shall provide continuous and uninterrupted measuring of pressure from the chamber or igniter.

The pressure train should be designed so that plugging by deposits of combustion residue will be eliminated, and continuous monitoring of pressure will be possible. Pressure train outlets should not be located in regions where particle impingement or deposition and collection of combustion residue appears likely. Small diameter (less than three-sixteenth inch) inlet holes should be avoided, if possible, because of a greater tendency for small holes to plug. Large-diameter (more than about three-eighths inch) holes should also be avoided because of the problems mentioned in sections 3.2.2.2 and 3.2.2.4. Redundant pressure trains are desirable and should be employed. Strain gages should be attached to the motor case surface for the purpose of deriving pressure data in the event the conventional pressure transducers fail.

3.2.2.6 Detection of Pressure Oscillations

The locations for monitoring pressure shall ensure that acoustic oscillations are measured.

Optimum placement of pressure transducers for measurement of longitudinal and axial mode oscillations should be at either end of a motor, since every longitudinal mode has a pressure antinode at these locations. Optimum placement of pressure transducers for detection of transverse mode oscillations presents a problem because the locations of the pressure antinodes follow the regression of the propellant web. Recommended locations to provide information or orientation of tangential mode acoustic oscillations are shown in figure 30; comparison of outputs from the three transducers will identify acoustic oscillations of all three types, i.e., longitudinal, radial, and tangential oscillations. A pressure transducer on the motor axis theoretically cannot detect a tangential mode (ref. 41); therefore an axial location should be avoided.

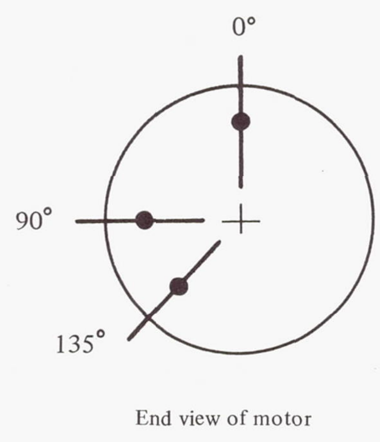


Figure 30.—Recommended pressure transducer locations for acoustic oscillations.

3.2.3 Temperature and Heat Flux

3.2.3.1 Range and Capacity

The capacity of a thermocouple or a calorimeter shall be adequate to measure the range of temperature or heat flux expected during testing.

The maximum temperature to be monitored during or after a test (considering soak temperatures) should be carefully assessed, and a thermocouple selected accordingly. The maximum temperatures for the materials listed in section 2.2.3.1 should not be exceeded during or after testing.

Heat-flux calorimeters should be used in their proper calibration ranges. With low-range calorimeters, overloads to about 200 percent are permissible for short periods of time. A calorimeter should have the same spectral absorptivity, emissivity, and temperature history (ref. 73) as the surface it is monitoring; otherwise, the data will not give an accurate indication of the true flux absorbed by the surface.

3.2.3.2 Response Time

Temperature and heat-flux sensors shall have response times commensurate with motor test requirements.

Thermocouple wire should be as small as practical for the particular installation. As mentioned in section 3.2.2.5, installations in ablative insulation require wire with a small diameter; AWG 36 or 40 should be used. For other applications, such as on the outside surface of the motor, use a larger diameter wire (AWG 24 to 30) because of its greater mechanical strength provided that its slower response time can be tolerated.

When using calorimeter data, recognize that the response time of low-range calorimeters may approach 1 second or more, depending upon physical size and type of calorimeter.

3.2.3.3 Location

The locations of thermocouples and calorimeters shall ensure that temperatures and heat fluxes are monitored in all critical areas.

Regions that have minimum safety factors or are subjected to unknown thermal environments during testing are the primary locations. Areas of maximum thermal stresses, areas near char or erosion fronts, areas having low design margins for thermal degradation, and areas with poorly defined properties for design are locations that are thermally critical. As a minimum, these locations should be monitored. For the reasons noted in section 3.1.6.4, monitoring the solid-propellant temperature just prior to ignition is usually important.

3.2.3.4 Placement

The placement of temperature and heat-flux sensors shall be accurate and reproducible from test to test.

The position of a thermocouple junction should be known with a high order of accuracy. For example, when a thermocouple is embedded in either nozzle or case insulation, the junction depth should be known within ± 0.003 in. or less; longitudinal and transverse position should be known within ± 0.1 in., or less if possible. Physical measurement of a junction position by depth gages is recommended. When this is not possible, X-ray or other suitable techniques should be employed, and care must be taken to minimize parallax errors. Postfire sectioning of hardware to locate a junction position is recommended for verification of a measuring site.

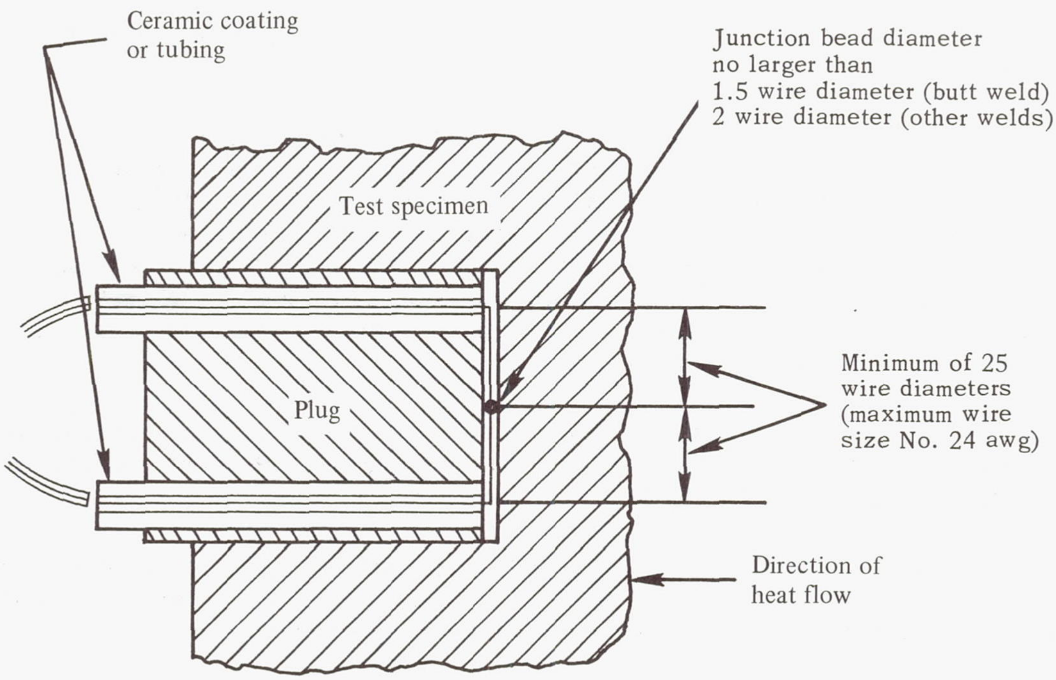
The position of a heat-flux calorimeter should be known within ± 0.1 in., or less, in the longitudinal and transverse directions on a motor surface. Position verification by direct measurement is recommended.

Thermocouples and calorimeters should monitor identical locations in repetitive tests to permit a valid comparison of data; the use of a location gage or template is recommended to ensure that placement will be essentially the same from test to test.

3.2.3.5 Reduction of Thermal Disturbance

Thermal disturbance by a sensor at the monitored location shall be at a minimum.

To minimize disturbance of the true temperature field by a sensor, the use of small-diameter thermocouple wire is recommended; wire sizes from a maximum of AWG 24 to a minimum of AWG 36 or 40 should be utilized. For applications in low-conductivity ablative material, the smaller wire, AWG 36 or 40, is preferred (ref. 74). To minimize heat conduction away from an internal junction in ablative material, it is recommended that the configuration of the thermocouple sensor be such that the leads perpendicular to the heat flow will have a length equivalent to at least 25 wire diameters on both sides of the junction in the same isothermal surface that includes the hot junction. The recommended thermocouple bead diameter is less than 1.5 wire diameters for butt-welded junctions and less than 2 wire diameters for other types of welds. The holes drilled for placement of thermocouple wire should be equivalent to or less than 3 wire diameters. Good thermal contact and elimination of air pockets between ablative material and wire should be achieved by bonding with a suitable adhesive. Figure 31 presents a summary of recommended practices and shows that the plug material should be the same as the test specimen. Surface-mounted calorimeters that measure radiant heat flux should be flush with the surface. Any unavoidable protrusion should be restricted to the smallest possible dimensions. Junctions of surface-mounted thermocouples should be in direct contact with the surface; there should be no bonding adhesive between the junction and the surface.



Notes:
(1) Plug and test specimen of same material
(2) Plug, thermocouple and junction bonded to test material with same or similar compound used to make test specimen.

Figure 31.—Recommended practices for mounting thermocouples—plug type specimen.

3.2.3.6 Protection From Char and Erosion

Charring, ablation, or erosion of rocket motor components shall not impair sensor accuracy.

Loss of thermocouple signal by electrical conduction through a char layer should be prevented by using small ceramic tubes or a ceramic coating as electrical insulation.

Figure 31 shows the use of ceramic electrical insulation for a plug-type thermocouple. The ceramic diameter should be small enough to conform to the recommendations of section 3.2.3.5; i.e., the holes drilled for placement of thermocouple wire should be equivalent to no more than 3 wire diameters. When measuring the surface temperature of charring and eroding ablative material, use an erodible-sandwich-type surface thermocouple (fig. 23).

3.2.3.7 Protection From Radiant Heat

Radiant heating shall not impair sensor accuracy.

Thermocouples mounted on the outside surface of a motor case or nozzle for measuring heat soak from within should be protected from radiant heat by a layer of suitable insulation; RTV rubber has proven satisfactory and is recommended. An example of such protection for thermocouples is shown in figure 21(a). It is recommended that the lead wires also be protected from radiant heat as shown in figure 21(a).

3.2.4 Strain, Deflection, and Elongation

3.2.4.1 Range and Capacity

The capacity of strain gages, linear potentiometers, and other motion sensors shall be adequate to measure the range of strain, deflection, or elongation expected during testing.

When strain gages are to be applied to very ductile or plastic materials, a post-yield-type gage with lengths of one-half inch and up is recommended for monitoring strains up to about 5 percent; for shorter gage lengths, one-quarter inch and less, the allowable strain is about 1 percent. When potentiometers are used to measure deflections and elongations, the total movement must not exceed the allowable range. To acquire all possible data, make a careful assessment of the maximum expected displacement, the type of measurement desired, and the nature of materials being tested; then select the motion transducers accordingly.

3.2.4.2 Location

The location of motion sensors shall ensure that all areas of critical stress or regions of high strain are monitored.

Design analyses or prior experience generally will indicate specific locations. Typical locations are shown in figures 24, 25, and 26. Glass-filament-wound chambers should be monitored at the dome/cylinder interfaces, dome/pole piece regions, and chamber/cylinder regions. Metal chambers should be monitored at welded seams and at dome/cylinder interfaces. Nozzle-attachment-assembly locations and nozzle shells should be considered for transducer placement unless experience with a given design dictates otherwise.

3.2.4.3 Alignment

Strain gage axes shall be parallel with the principal strains.

When the principal strain axes are known and the strain data are to be used for calculating stresses, a two-element gage should be utilized. When the directions of principal strain are unknown, a three-element, rosette-type gage should be used to resolve the principal strain directions and magnitudes.

3.2.4.4 Size

The physical size of a strain gage shall be commensurate with the strain gradient in the monitored location.

A strain gage should be small enough to fit into a field of nearly uniform strain. As noted previously, maximum strains are not sensed, and a gage provides averaged values for the strains to which it is subjected. When it is necessary to monitor steep strain gradients, the smallest gage possible (about 1/16-in. gage length) should be used, and it should be placed as near the maximum strain point as possible. When steep strain gradients are not present, the largest strain gages are recommended because of their greater accuracy.

3.2.4.5 Attachment

Attachment of a motion sensor shall be adequate for the strain or elongation being measured and appropriate for the mounting surface.

Most of the causes of poor or inadequate attachment of motion sensors were cited previously. These sources of trouble should be recognized and avoided.

Bonding of strain gages to glass-filament-wound chambers should follow established and recommended procedures using specially selected adhesive (ref. 75). Application of gages to metal chambers should be accomplished by following the gage manufacturer's recommended procedures, using the recommended strain-gage cements.

Generally, the shaft of a linear potentiometer should be perpendicular to the surface being monitored. The surface that is contacted by the tip of a linear potentiometer shaft should be as smooth as possible to ensure that shaft movement will not be hindered. A piece of Teflon tape should be used over rough surfaces.

3.2.4.6 Placement

The placement of a motion sensor shall be accurate and reproducible from test to test.

Motion sensors should be placed within ± 0.10 in. or less of the desired position. Strain-gage and linear-potentiometer placement should be consistent from test to test so that a valid comparison of cross-test data is possible. Mounting brackets, special tooling, templates, or location gages should be employed to place motion sensors accurately.

3.2.4.7 Calibration

The calibration of a motion sensor shall be current and accurate.

Motion sensors should be calibrated physically by measured deflections. Height gages that are calibrated periodically (preferably every 2 months) with standard gages should be used to calibrate linear potentiometers. It is recommended that the standard gages be calibrated by the National Bureau of Standards, or an equivalent authority, at least every year. Strain gages should be calibrated electrically with precision resistors connected in parallel with the gages to simulate strain, and a bridge circuit (ref. 76) should be used to measure the change of electrical resistance. The gage factor that relates changes of resistance with changes of strain, as specified by the gage manufacturer, should be known accurately.

3.2.4.8 Protection From Thermal Environment

The thermal environment during testing shall not impair the accuracy of motion sensor measurements.

Insulation or heat shields should be employed unless careful analysis or experience dictates otherwise. A cork pad or RTV rubber should be used for bonding over strain gages to provide thermal insulation. Zinc chromate putty and aluminum foil, or equivalents, should be used to protect linear potentiometers (fig. 24).

3.2.4.9 Temperature Compensation

Temperature changes shall not impair the accuracy of strain gage measurements.

A second identical gage (dummy gage) should be used whenever possible to cancel the effect of temperature changes upon the resistance of the active gage; this arrangement results in a Wheatstone bridge balance that will be responsive to mechanical strain imposed on the active gage. Self-temperature-compensating gages should be employed when it is impossible to subject a dummy gage to identical temperature variations. These compensating gages should be selected to match the thermal coefficient of expansion of the material being measured.

3.2.5 Shock and Vibration

3.2.5.1 Range and Capacity

The capacity of a shock and vibration accelerometer shall be adequate to measure the range of the dynamic environment anticipated during testing.

The maximum dynamic range of shock and vibration to be measured during a test should be carefully assessed and an accelerometer selected accordingly to avoid non-linearity, hysteresis, or damage. Piezoelectric accelerometers should be used when over 500 g are expected. It is recommended that a selected accelerometer be subjected to peak accelerations that are less than those specified by the manufacturer. Large static or steady over-accelerations are usually allowable for strain-gage-type accelerometers; specified over-accelerations should not be exceeded.

3.2.5.2 Frequency Response

Accelerometers shall have a frequency response adequate to measure anticipated shock and vibration.

A system having flat response to 10,000 Hz should be sufficient to record all shock and vibration likely to be encountered during testing. Generally, the required frequency response depends on the rise time or duration of the shocks to be measured. When the form or shape of expected shock is known, a system with a smaller band width may be satisfactory. Additional considerations and recommendations involving adequate frequency response are given in reference 77, pp. 12-7 to 12-10 and 16-13 to 16-18.

3.2.5.3 Critical Locations

Location of accelerometers shall ensure that shock and vibration are monitored at all critical areas.

The following locations of an accelerometer on the motor structure are recommended: (1) forward and aft dome regions. (2) nozzle adapters, attach rings, and forward port and igniter adapters, (3) exit-plane region of nozzles, and (4) wherever sensitive components and instruments are mounted.

Shock and vibration measurements at positions where critical components will be located on the motor during flight may not be accurate if the component of interest is not mounted on the motor during the test. Dummy hardware components should be utilized to simulate the mass and stiffness of the actual hardware.

When the motor forms part of a spacecraft, the complete unit should be monitored. Reference 78 gives an example of spacecraft instrumentation.

3.2.5.4 Directional Placement

The alignment of accelerometers shall be adequate to measure the acceleration load accurately, and the placement shall be reproducible from test to test.

Accelerometers should be aligned in the direction of the acceleration vector to obtain an accurate assessment of the magnitude of the expected acceleration load. Both piezoelectric and strain-gage-type accelerometers have directional sensitivity, and data should be corrected if necessary by applying a factor to account for the amount of angular misalignment as described in reference 77, pp. 16-19 and 17-15.

Accelerometers should be placed accurately, within ± 0.10 in. or less; placement should be consistent from test to test to permit a valid comparison of cross-test data. Mounting brackets, special tooling, templates, and location gages should be employed, if necessary, to place accelerometers as close as possible to the location of maximum expected response. If the mode shape is unknown, use several accelerometers to avoid failure to acquire data by inadvertent location of a single sensor on a nodal point.

3.2.5.5 Attachment

The method of attaching accelerometers to the rocket motor shall ensure accurate shock and vibration data.

Accelerometers should be attached or torqued securely to obtain accurate measurement of high-frequency vibrations. Mounting surfaces should be smooth to permit good coupling between accelerometer and the surface to be monitored. If a mounting plate, jig, or fixture is employed, its influence should be assessed; e.g., a mounting fixture should not be used if it is subject to transverse acceleration that could excite resonances that usually occur at frequencies lower than those in the axial direction. The effective stiffness of the transducer mounting should be great in the frequency range of interest to prevent deflection under the inertia load of the transducer mass. General rules for transducer-mounting design to ensure accuracy of results are listed in reference 77, pp. 20-5 and 20.9.

Adhesive attachment of an accelerometer should be made only after adequate preparation and cleaning of the mating surfaces. A thin layer of adhesive should be used; a thick layer could result in partial decoupling because of the elasticity of the adhesive. Nonhardening or solvent-drying adhesives should not be employed because they act like soft springs and allow the transducer to decouple from the test surface (ref. 77, pp. 20-5 and 20-9).

3.2.5.6 Calibration

The calibration of accelerometers shall be current and accurate.

An accelerometer should be calibrated in the laboratory by a back-to-back shake test with a secondary standard (ref. 79). When accelerometers are mounted on a motor before testing, a simulated in-place calibration method using a series-voltage insertion is recommended (refs. 80 and 81).

3.2.5.7 Protection From Thermal Environment

The thermal environment during testing shall not impair the accuracy of the accelerometer measurements.

To protect accelerometers from changes in temperature during testing, thermal insulation or heat shields should be employed as necessary (sec. 3.1.6).

REFERENCES

1. Cingo, R. P.: A Rapid Method of Evaluating Thrust Stand Dynamic Response. CPIA No. 58A, ICRPG Solid Propellant Rocket Static Test Working Group, Addendum to Bulletin of the 2nd Meeting, Sept. 1964, p. 91.

*2. Anon.: HIBEX Development, January 1964—September 1965 (U). Dev. 6164, Hercules Powder Co., ABL (Cumberland, Md.). Unpublished, pp. II-10, 11; figure II-1A. (Confidential)

3. Anon.: 1965 Production Support Program Final Report (U). BSD TR-361, Vol. I, Hercules, Inc., June 1967, pp. 4-60. (Confidential)

4. Morey, L.: The Project Engineers' Viewpoint of Instrumentation Requirements (U). Proceedings of the Fourth Meeting of the Joint Army-Navy-Air Force Solid Propellant Rocket Static Test Panel, Oct. 12-14, 1955. (Confidential)

5. Miller, W. H.; and Barrington, D. K.: Contemporary Solid Rocket Motor Performance Prediction Techniques. AIAA Paper No. 69-732, AIAA 5th Prop. Joint Specialist Conf., USAF Academy, June 9-13, 1969.

6. Summerfield, M.; Foster, C.; and Swam, W.: Flow Separation in Over-Expanded Supersonic Exhaust Nozzles. ARS J., vol. 24, no. 5, Sept-Oct. 1954, pp. 319-321.

7. Barrere, M.: Rocket Propulsion. Elsevier Pub. Co., 1960, p. 77.

8. Kalt, S.; and Badal, D. L.: Conical Rocket Nozzle Performance Under Flow-Separated Conditions. J. Spacecraft Rockets, vol. 2, no. 3, May-June 1965, pp. 447-449.

9. Scheller, K.; and Bierlein, J.: Some Experiments on Flow Separation in Rocket Nozzles. ARS J., vol. 23, no. 1, Jan.-Feb. 1953, p. 28.

10. Lawrence, R. A.; and Weynand, E. E.: Factors Affecting Flow Separation in Contoured Supersonic Nozzle. AIAA J., vol. 6, no. 6, June 1968, p. 1159.

11. Lucy, M. H.; Northan, G. B.; and Swain, R. L.: Rocket Motor Spin Data Summary. TP 3770, Symposium on Behavior of Propellants under Acceleration Fields, Naval Ordnance Test Station, China Lake, Calif., June 1965.

12. Manda, L. J.: Final Report, Compilation of Rocket Spin Data. Vol. II: Literature Survey. NASA CR-66641, 1968.

13. Lucy, M. H.: Spin Acceleration Effects on Some Full-Scale Rocket Motors. J. Spacecraft Rockets, vol. 5, no. 2, Feb. 1968, p. 179.

---

*Addendum to the Dossier for Design Criteria Monograph on Captive-Fired Testing of Solid Rocket Motors (U). Unpublished, 1968. Collected source material available for inspection at the Lewis Research Center, Cleveland, Ohio. (Confidential)

14. Willoughby, P. G.; and Crowe, C. T.: Investigation of Internal Ballistic Effects in Spinning Solid Propellant Motors. UTC 2281-FR, United Technology Center, Oct. 1968, p. 2.

15. Bahor, L. R.; and Brooksbank, R. M.: Altitude Performance Evaluation of Thiokol TP-H-1092 Berylliuminized Propellant Tested in a Surveyor Main Retrorocket Motor Case (TU-363B) (U). AEDC-TR-68-195, ARO, Inc., Sept. 1968. (Confidential)

*16. Anon.: Static Test Firing Report for TU-465.01, High Performance 120-Inch Diameter Motor (U). TWR-1761, Thiokol Chem. Corp. (Wasatch Div.). Unpublished, Mar. 1966, p. 5-4. (Confidential)

17. Smallwood, W. L., et al.: Beryllium Erosion Corrosion Investigation for Solid Rocket Nozzles, Final Report (U). AFRPL-TR-67-82, Space and Re-entry Systems Div., Philco-Ford Corp., June 1967. (Confidential)

*18. Anon.: Final Report for Hercules BE-3-C1 Motor Demonstration Motor Program (U). MTO-1124-2, Hercules, Inc. (Magna, Utah). Unpublished, May 1967, p. 9. (Confidential)

19. Anon.: Composite Beryllium Propellant Motors for Project Adobe, Final Report (U). BSD-TR-66-359, Wasatch Div., Thiokol Chemical Corp., Dec. 1966, figs. 100-104. (Confidential)

*20. Anon.: Final Test Report, TU-455.01 Rocket Motor, Submerged Gimbal Nozzle (U). TRW-962, Thiokol Chem. Corp. (Wasatch Div.). Unpublished, May 1965, p. 35. (Confidential)

*21. Anon.: Final Test Report, TU-455.02 Rocket Motor Submerged Gimbal Nozzle (U). TRW-1399, Thiokol Chem. Corp. (Wasatch Div.). Unpublished, Oct. 1965, p. 83. (Confidential)

22. Anon.: Fourth Quarterly Technical Progress Report on the Demonstration of Advanced Technology in a High-Performance Solid Propellant Motor (U). ARC-QPR4-26A1 (AD-353052), Atlantic Research Corp., Aug. 1964. (Confidential)

23. Smallwood, W. L., et al.: Beryllium Erosion Corrosion Investigation for Solid Rocket Nozzles—Fourth Technical Progress Report (U). AFRPL-TR-67-16, Space and Re-entry Systems Div., Philco-Ford Corp., Feb. 1967, pp. 67-72. (Confidential)

*24. Anon.: Hercules Incorporated/Thiokol Chemical Corporation (A Joint Venture), Subsystem Test Report, Poseidon C3 Second Stage Simulated Altitude Static Test SD-0019 (U). Rep. 19, LMSC Data Item No. SHO49-A2A00HTJ. Unpublished, Sept. 1968, pp. 27-28. (Confidential)

25. Cimino, A. A.; and Stevenson, C. W.: Results of the Qualification Test of Eight JPL-SR-28-3 Rocket Motors at Simulated Altitude. AEDC-TR-66-221, (AD802218), Arnold Engineering Development Center, Nov. 1966.

26. Anon.: Qualification Phase for the Applications Technology Satellite Apogee Rocket Motor. JPL Tech. Memorandum 33-339, N68-24001, Jet Propulsion Lab, Sept. 15, 1967.

*Addendum to the Dossier for Design Criteria Monograph on Captive-Fired Testing of Solid Rocket Motors (U). Unpublished, 1968. Collected source material available for inspection at the Lewis Research Center, Cleveland, Ohio. (Confidential)

*27. Haselberger, F. E., Jr.: Polaris Static Firing Report (U), RH-427, Firing Date, February 7, 1962. Hercules Powder Co., ABL. Unpublished, Oct. 1962, p. 3. (Confidential)

*28. Haselberger, F. E., Jr.: Polaris Static Firing Report (U), B-622, Firing Date, March 22, 1962. Hercules Powder Co., ABL. Unpublished, Nov. 1962, p. 2. (Confidential)

29. Anon.: Final Report, Wing II Continued Development, Firing Number 243D-2-1-63, Weapon Systems 133-A Rocket Motor M-57-E1 (U). MTO-164-111, Hercules Powder Co., Jan. 1962, p. 5. (Confidential)

30. Dickinson, L. A.; Jackson, F.; and Odgers, A. L.: Erosive Burning of Polyurethane Propellants in Rocket Engines. Eighth Symposium (International) on Combustion, Williams and Wilkins Co., 1962, pp. 754-759.

31. Osborn, J. R.; and Bethel, H. E.: Techniques for Measuring Burning Rates of Solid Propellants, Rev. Sci. Instr., vol. 35, no. 9, Sept. 1964, pp. 1130-1134.

32. Anon.: Demonstration of High Thrust Hybrid Thrust Chamber Assembly. AFRPL-TR-68-56, United Technology Center, Apr. 1968, pp. 93 and 120.

33. Jenks, J. C.; and Devault, J. B.: Microwave Measurements of Solid Propellant Burning Rates and Burning Profiles (U). Bulletin of the 1st Meeting, ICRPG Working Group on Static Testing, CPIA No. 24, Sept. 1963, pp. 311-319. (Confidential)

34. Bond, D. L.: Rocket Motor Testing at the Augmented Altitude Facility at the Jet Propulsion Laboratory (U). Bulletin of the 1st Meeting, ICRPG Working Group on Static Testing, CPIA No. 24, Sept. 1963, pp. 185-196. (Confidential)

35. Cholley, D.: Factors to be Considered in Extending Present Thrust Stand Designs for Measurement of Effects of Intricate High Frequency Nozzle Programs (U). Bulletin of the Eighth Meeting of the JANAF Solid Propellant Rocket Static Test Panel, Nov. 1959, pp. 139-164. (Confidential)

36. Jessup, H. A.: The Thrust Stand—New to the Limelight (U). Bulletin of the Tenth Meeting JANAF Solid Propellant Rocket Static Test Panel, Oct. 18-20, 1961, pp. 163-174. (Confidential)

37. Johnson, W. O.: Accuracy Investigation of Fluid Bearing Static Test Stand (U). CPIA No. 91, ICRPG Solid Propellant Rocket Static Working Group, Bulletin of 3rd Meeting, Sept. 1965, pp. 67-85. (Confidential)

38. Thomson, T. B.: The Effect of Tubing on Dynamic Pressure Recording. TR-61-3 (AD-459777). Rocketdyne, Feb. 1961, p. 29.

39. Inskeep, J.: Dynamic Testing of Pressure Transducers—A Progress Report. JPL Tech. Report No. 32-268, Jet Propulsion Laboratory, Dec. 6, 1961.

*Addendum to the Dossier for Design Criteria Monograph on Captive-Fired Testing of Solid Rocket Motors (U). Unpublished, 1968. Collected source material available for inspection at the Lewis Research Center, Cleveland, Ohio. (Confidential)

40. Jones, H. B.: Transient Pressure Measuring Methods. Aeronautical Engineering Report 595a, N62-10071, Princeton Univ., Jan. 1962.

41. Mathes, H. B.: Measurement Problems Related to Solid Rocket Combustion Instability (U). CPIA No. 161, ICRPG Solid Propellant Rocket Static Test Working Group, 5th Meeting, Oct. 18-20, 1967, pp. 45-61. (Confidential)

42. Moeller, C. E.; Noland, M.; and Rhodes, B. L.: NASA Contributions to Development of Special-Purpose Thermocouples. NASA SP-5050, 1968, pp. 46-47.

43. Beck, James V.: Thermocouple Temperature Disturbance in Low Conductivity Material. Trans. ASME, J. Heat Transfer, Series C, vol. 84, 1962, pp. 124-132.

44. Dow, Marvin B.: Comparison of Measurements of Internal Temperatures in Ablation Materials by Various Thermocouple Configurations. NASA TN D-2165, 1964.

45. Moen, W. K.: Significance of Errors in High Temperature Measurement. SAE Paper No. 750F, AIAA Paper No. A63-23854, presented at National Aeronautic and Space Engineering and Manufacturing Meeting (Los Angeles), Sept. 23-27, 1963.

46. Beck, J. V.: Study of Thermal Discontinuities and Associated Temperature Disturbances in a Solid Subject to a Surface Heat Flux. Part III—Effect of Sensors in Low Conductivity Material Upon Temperature Distribution and Its Measurement. Tech. Report RAD-TR-9(7)-59-26, Avco Corp., Oct. 1959.

47. Stein, P. K.: Adhesives: How They Determine and Limit Strain Gage Performance. Preprint 7-NY60, Instrument Society of America Conference (New York City), Sept. 26, 1960.

48. Perry, C. C.; and Lissner, H. R.: The Strain Gage Primer. McGraw-Hill Book Co., 1955, p. 165.

49. Oleson, M. W.: Application of a Special Test Fixture to Vibration Measurement During Static Firing of Rocket Motors. NRL Memorandum Report 1039, Naval Research Lab., Washington, D.C., Apr. 1960.

50. Trummel, M.: Application of Static-Test Vibration Data (U). Tenth Meeting Bulletin, JANAF Solid Propellant Rocket Static Test Panel, Oct. 1961, pp. 211-227. (Confidential)

51. Tustin, Wayne: Acceleration Calibration Methods. Test Engineering and Management, vol. XI, no. 3, Mar. 1964, pp. 13-44 (intermittently).

52. Johnson, W. O.: Transient Response of a Rocket Motor Test Stand (U). Bulletin of 2nd Meeting, Solid Propellant Rocket Static Test Working Group, ICRPG, Sept. 1964, p. 133. (Confidential)

53. Lightner, I. C.: Simulated High-Altitude Testing of Solid Propellant Rockets (U). 10th Meeting Bulletin, JANAF Solid Propellant Rocket Panel, Oct. 1961, pp. 113-150. (Confidential)

54. Northam, G. B.; and Lucy, M. H.: On the Effects of Acceleration Upon Solid Rocket Performance. AIAA Paper No. 68-530, presented at ICRPG/AIAA 3rd Solid Propulsion Conference (Atlantic City), 1968.

*55. Reynolds, K. B.; and Zeamer, R. J.: An Analysis of Metal Agglomerate Deposition in the Aft Dome of the X259 C3 and 74-Inch Demonstration Motors (U). MISC/6/40-356, Hercules, Inc. (Magna, Utah). Unpublished, Sept. 1967. (Confidential)

56. Markstein, G. H.: Combustion of Metals. AIAA J., vol. 1, no. 3, Mar. 1963, pp. 550-62.

*57. Anon.: Final Report for Hercules X259 C3 Motor, Demonstration Program (U). MTO-1024-1B, Hercules, Inc. (Magna, Utah). Unpublished, Sept. 1967, p. 10. (Confidential)

*58. Anon.: Composite Beryllium Propellant Motors for Project Adobe (U). Final Report, BSD-TR-66-359. Thiokol Chem. Corp. (Wasatch Div.). Unpublished, Dec. 1966, p. 71. (Confidential)

*59. Anon.: Polaris Firing and Evaluation Report, RH-368 (U). Hercules Powder Co., ABL. Unpublished, Feb. 1964, p. 10. (Confidential)

*60. Anon.: Polaris Firing Data Book (U), Motor RH-374. Hercules Powder Co., ABL. Unpublished, Apr. 30, 1964, p. 2. (Confidential)

61. Morizumi, S. J.; and Carpenter, H. J.: Thermal Radiation from the Exhaust Plume of an Aluminized Composite Propellant Rocket. J. Spacecraft Rockets, vol. 1, no. 5, Sept.-Oct. 1964, pp. 501-507.

62. Thorn, W. F.; and Randle, D. K.: High Altitude Testing of Large Rocket Engines (U). CPIA No. 24, Bulletin of the 1st Meeting, ICRPG Working Group on Static Testing, Sept. 1963, pp. 197-212. (Confidential)

†63. Farmer, M. E.; and Brands, E. R.: Thermally Reflective Finishes for WS-133B Flight Control Hardware. TR-64-233, Autonetics Div., North American Aviation. Unpublished, Mar. 1964.

64. Sjostrom, C. R.; and Macpherson, H. R.: Amrad Fourth Stage BE-3-A5 Rocket Motor, Final Report (U). Report No. HPC-230-12-3-9, AD-368774, Hercules Inc., Jan. 1966, p. 13. (Confidential)

65. Geothert, B. Y.: High Altitude and Space Simulation Testing. ARS J, vol. 32, no. 6, June 1962, pp. 872-882.

66. Lightner, I. C.: Simulated High Altitude Testing of Solid Propellant Rockets (U). Tenth Meeting Bulletin, JANAF Solid Propellant Rocket Static Test Panel, Oct. 18-20, 1961, p. 118. (Confidential)

*Addendum to the Dossier for Design Criteria Monograph on Captive-Fired Testing of Solid Rocket Motors (U). Unpublished, 1968. Collected source material available for inspection at the Lewis Research Center, Cleveland, Ohio. (Confidential)

†Dossier for Design Criteria Monograph on Captive-Fired Testing of Solid Rocket Motors, Unpublished, 1968. Collected source material available for inspection at Lewis Research Center, Cleveland, Ohio.

67. Page, R. H.; and Dixon, R. J.: Base Heating on a Multiple Propulsion Nozzle Missile. Paper No. 63-179, presented at AIAA Summer Meeting (Los Angeles), June 17-20, 1963.

68. Stone, L. E.: Minutes of the Sixth ICRPG Test Stand Committee Meeting (U). CPIA No. 161, Solid Propellant Rocket Static Test Working Group 5th Meeting, Dec. 1967, p. 5. (Confidential)

69. Jessup, H. A.: Methods of Improving Frequency Response of Solid Propellant Rocket Motor Thrust Stands (U). CPIA No. 182, Bulletin of the 6th Meeting, Solid Propellant Rocket Static Test Working Group, Oct. 1968, pp. 17-30. (Confidential)

70. Anon.: Test Stand Calibration Procedure. HD-CP-2-4005. Hercules Data—Chemical Propulsion Div., Hercules Inc., Apr. 1968 (Available only from Hercules Inc.).

71. Stone, L. E.: Results of the ICRPG Multicomponent Test Stand and Spin Testing Committee Meeting—June 1966 (U). CPIA No. 124, Solid Propellant Rocket Static Test Working Group 4th Meeting Bulletin, Sept. 1966, p. 136. (Confidential)

72. Davis, R. L.: Techniques for Successful Six-Component Force Measurements of Rocket Motors. AEDC-TR-65-95 (AD-463226), Arnold Engineering Development Center, May 1965.

73. Brookley, C. E.: Proposed Method for Measuring Heat Flux Using a Circular Foil Calorimeter. Currently under acceptance procedures by ASTM Committee E-21 on Space Simulation, May 1968. (Available from author at Allegany Ballistics Lab, Hercules Inc.)

74. Grindle, S. L.; and Koubek, F. J.: Recommended Practice for Internal Temperature Measurements in Ablative Materials. ASTM: E 377-68, August 1968, General Test Methods, Part 30, ASTM Standards, May 1969.

75. West, G.: Evaluation of Strain Gages and Adhesives for Filament Wound Fiberglass Rocket Cases (U). Tenth Meeting Bulletin, JANAF Solid Propellant Rocket Static Test Panel, Oct. 18-20, 1961, pp. 67-73. (Confidential)

76. Woody, R. F., Jr.: Economical Calibration of Strain Gage Instrument Calibration (U). Bulletin of Third Meeting, ICRPG Solid Propellant Rocket Static Test Working Group, CPIA No. 91, Sept. 1965, pp. 87-92. (Confidential)

77. Harris, C. M.; and Crede, C. E.: Shock and Vibration Handbook. Vol. I. McGraw-Hill Book Co., 1961.

78. Domal, A. F.: Thermal and Dynamic Investigation of the Hughes ATS Spacecraft and Apogee Motor System at Simulated High Altitude. AEDC-TR-66-170, AFSC, Arnold Air Force Station, Oct. 1966.

79. Anon.: Instructions for Series 2200 Accelerometers. Endevco Corp. (Pasadena, Calif.).

80. Rhodes, J. E.: Piezoelectric Transducer Calibration Simulation Methods Using Series Voltage Insertion. Environmental Quarterly, vol. 8, April 1962.

81. Pennington, D.: In-Place Calibration of Piezoelectric Crystal Accelerometer Amplifier Systems. Paper presented at 6th I.S.A. National Flight Test Instrumentation Symposium (San Diego, Calif.), May 1960.

NASA SPACE VEHICLE DESIGN CRITERIA MONOGRAPHS ISSUED TO DATE

ENVIRONMENT

SP-8005	Solar Electromagnetic Radiation, June 1965
SP-8010	Models of Mars Atmosphere (1967), May 1968
SP-8011	Models of Venus Atmosphere (1968), December 1968
SP-8013	Meteoroid Environment Model—1969 (Near Earth to Lunar Surface), March 1969
SP-8017	Magnetic Fields—Earth and Extraterrestrial, March 1969
SP-8020	Mars Surface Models (1968), May 1969
SP-8021	Models of Earth's Atmosphere (120 to 1000 km), May 1969
SP-8023	Lunar Surface Models, May 1969
SP-8037	Assessment and Control of Spacecraft Magnetic Fields, September 1970

STRUCTURES

SP-8001	Buffeting During Atmospheric Ascent, revised November 1970
SP-8002	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	Flutter, Buzz, and Divergence, July 1964
SP-8004	Panel Flutter, May 1965
SP-8006	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	Buckling of Thin-Walled Circular Cylinders, revised August 1968
SP-8008	Prelaunch Ground Wind Loads, November 1965

SP-8009	Propellant Slosh Loads, August 1968
SP-8012	Natural Vibration Modal Analysis, September 1968
SP-8014	Entry Thermal Protection, August 1968
SP-8019	Buckling of Thin-Walled Truncated Cones, September 1968
SP-8029	Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent, May 1969
SP-8031	Slosh Suppression, May 1969
SP-8032	Buckling of Thin-Walled Doubly Curved Shells, August 1969
SP-8035	Wind Loads During Ascent, June 1970
SP-8040	Fracture Control of Metallic Pressure Vessels, May 1970
SP-8046	Landing Impact Attenuation For Non-Surface-Planing Landers, April 1970

GUIDANCE AND CONTROL

SP-8015	Guidance and Navigation for Entry Vehicles, November 1968
SP-8016	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8018	Spacecraft Magnetic Torques, March 1969
SP-8024	Spacecraft Gravitational Torques, May 1969
SP-8026	Spacecraft Star Trackers, July 1970
SP-8027	Spacecraft Radiation Torques, October 1969
SP-8028	Entry Vehicle Control, November 1969
SP-8033	Spacecraft Earth Horizon Sensors, December 1969
SP-8034	Spacecraft Mass Expulsion Torques, December 1969

SP-8036	Effects of Structural Flexibility on Launch Vehicle Control Systems, February 1970
SP-8047	Spacecraft Sun Sensors, June 1970

CHEMICAL PROPULSION

SP-8025	Solid Rocket Motor Metal Cases, April 1970
SP-8048	Liquid Rocket Engine Turbopump Bearings, March 1971
SP-8051	Solid Rocket Motor Igniters, March 1971

NASA-Langley, 1971 —— 28